



Connections running through MINERvA cross section results

Rik Gran

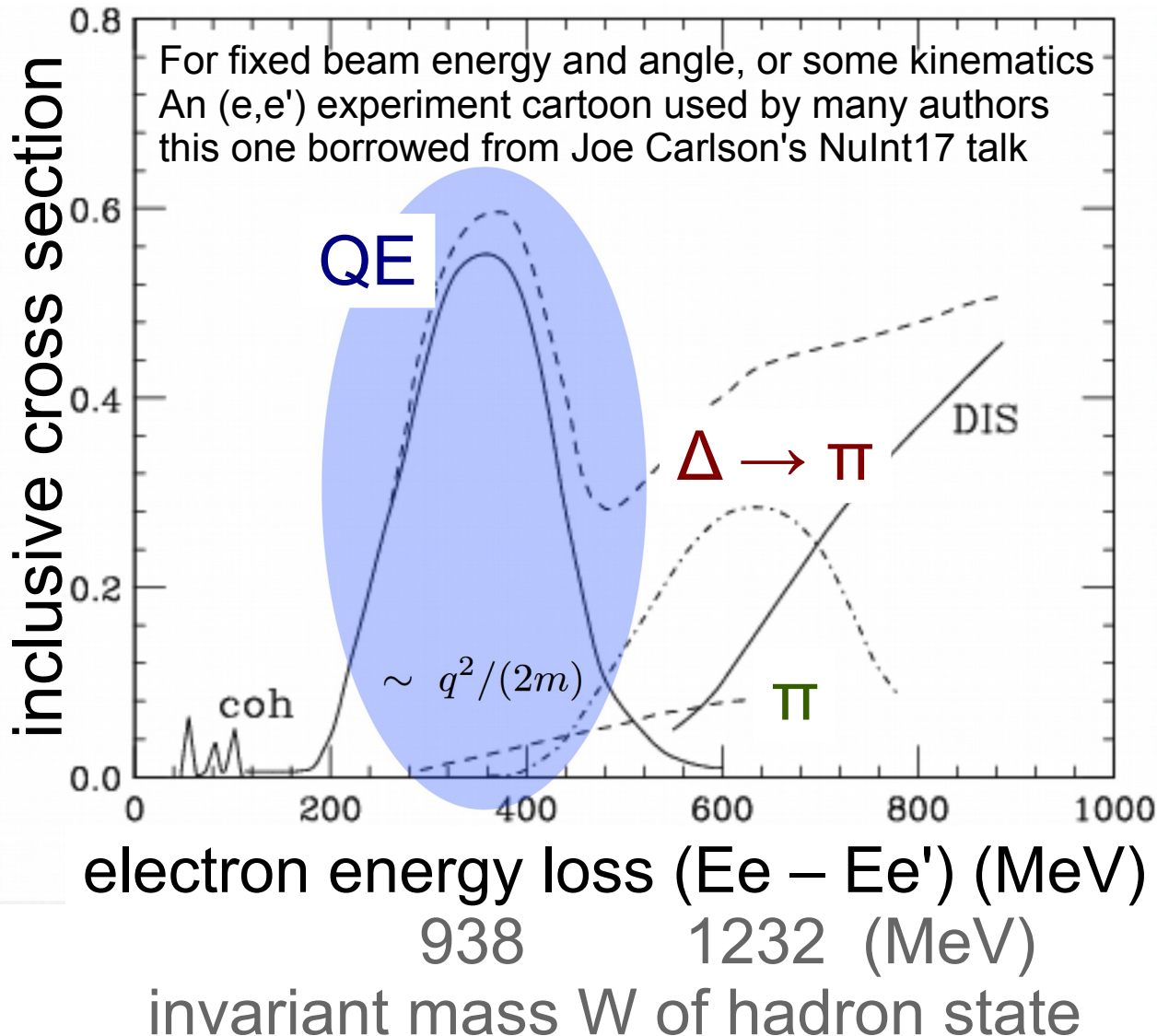
University of Minnesota Duluth

For the
MINERvA collaboration

**Saint Surrounded by
Three Pi Mesons**

Salvador Dalí
Figueres, Spain, 1957

Cartoon of topics and how they fit together



Inclusive low-recoil
quasielastic + **2p2h**
delta production + **2p2h**
pion production

neutrino vs. anti-neutrino
Pb/CH, Fe/CH, C/CH

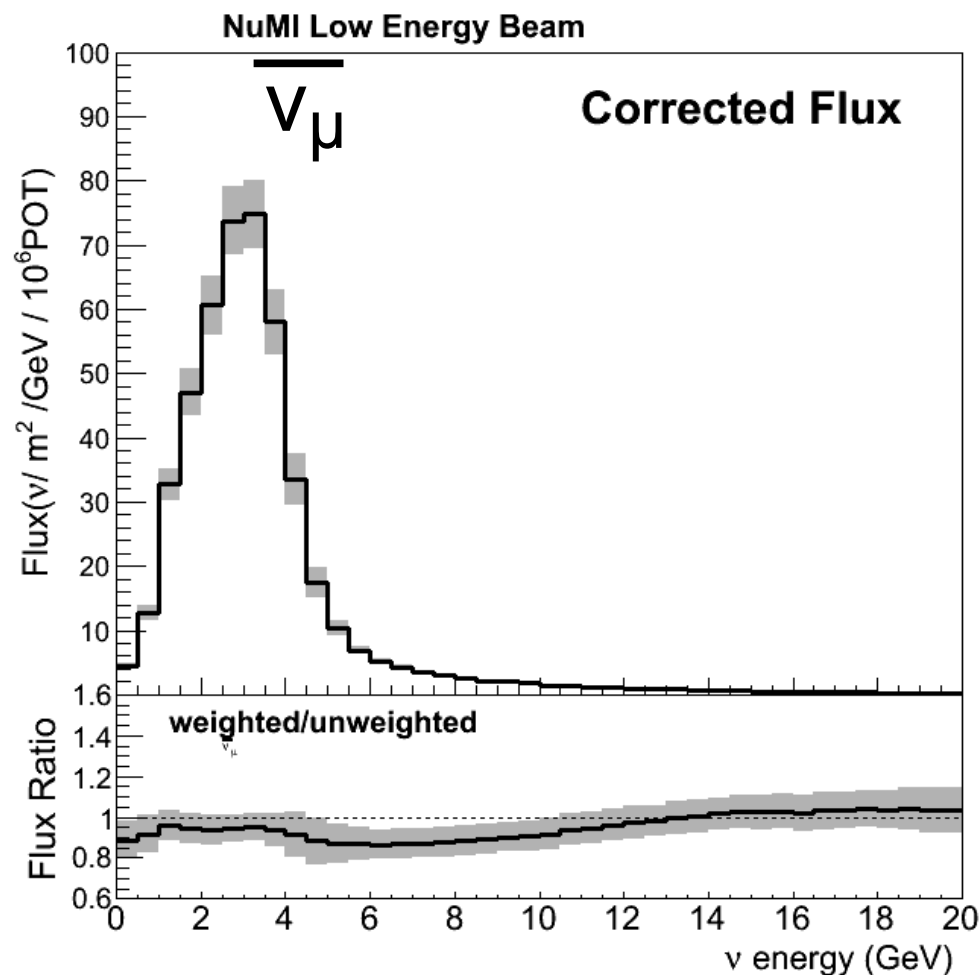
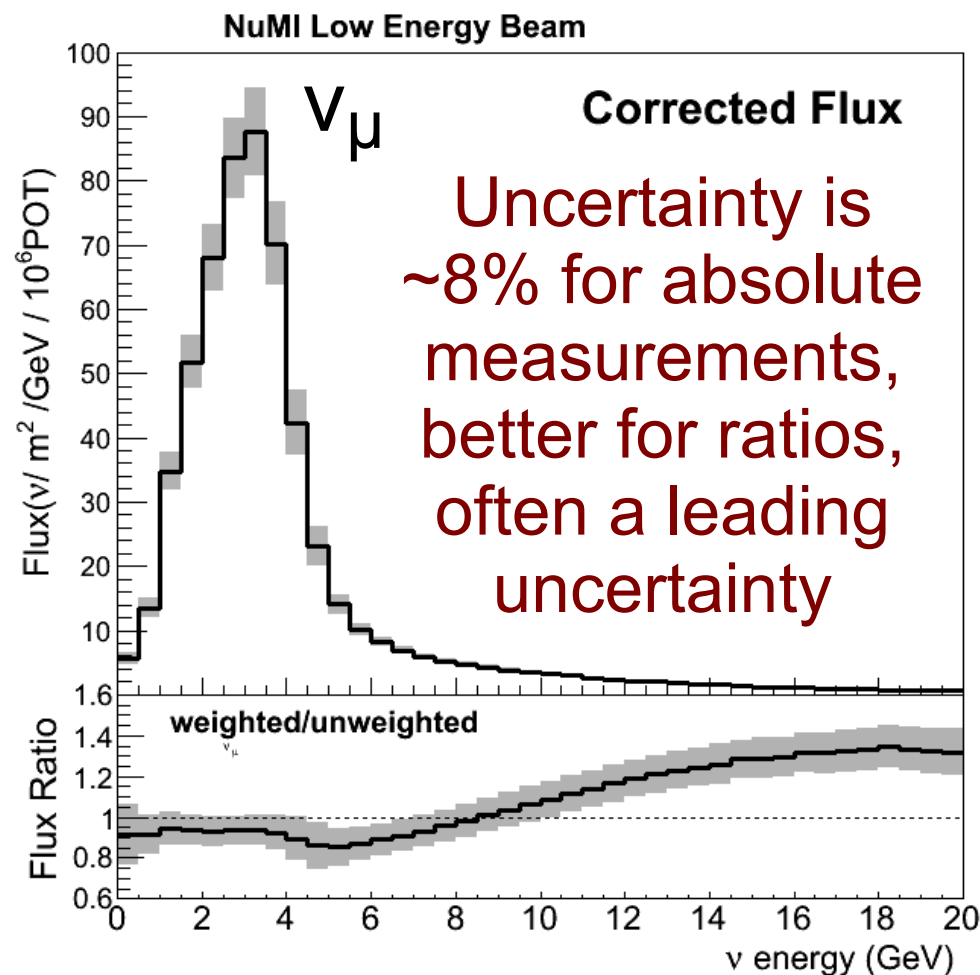
(Not in this talk, but lots of fun:
inclusive DIS and A-dependence
kaons, electron-neutrino,
medium energy running,
machine learning...)

The story today (2017), how well do we know this for neutrinos
interacting in Carbon, Iron, Lead, (Argon, Oxygen)

NuMI <3.5 GeV> beam has well characterized flux

L. Aliaga, M. Kordosky, T. Golan, [MINERvA], PRD 94 092005 (2016)

L. Aliaga ! Fermilab URA Outstanding Thesis Award 2016



Unweighted is original, ab-initio Geant4 simulation

Final flux based on hadron production and beam optics constraints

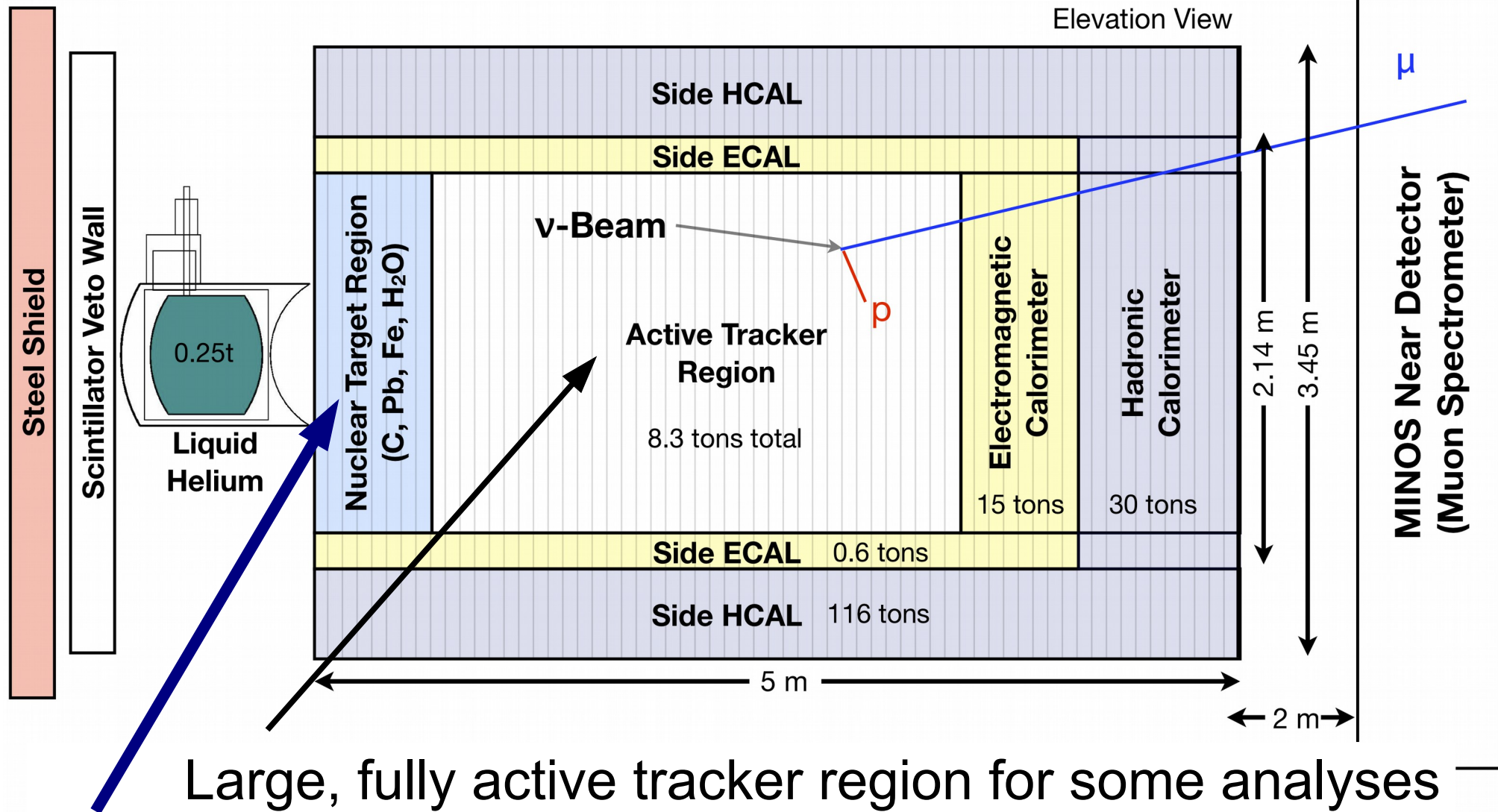
Denominator in our cross sections, large but simple uncertainty

Uncertainties mostly cancel for ratios!

MINERvA detector and nuclear target region

Detector is good at both tracking and calorimetry

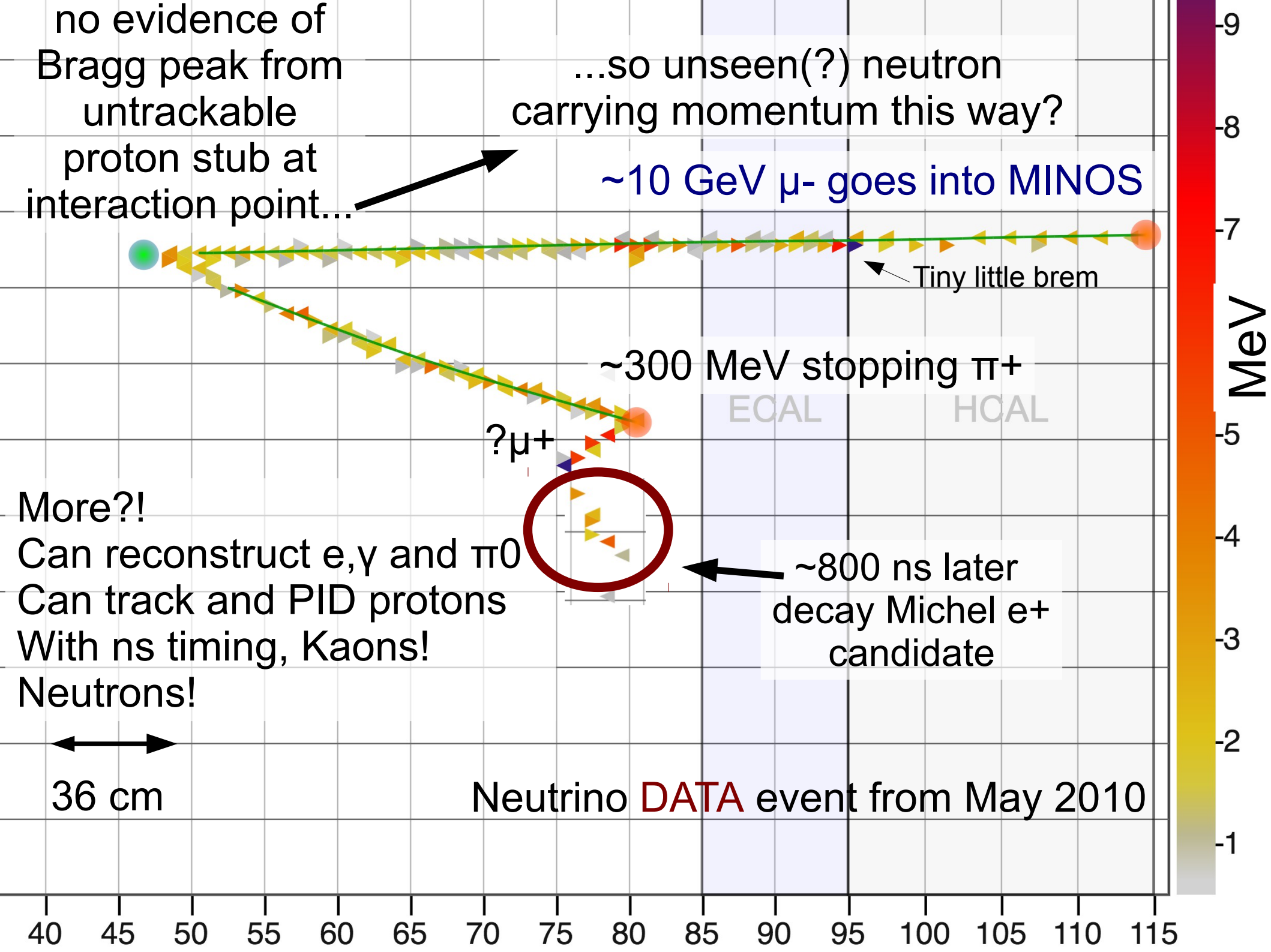
Reverse MINOS magnet too for anti-neutrino



Large, fully active tracker region for some analyses

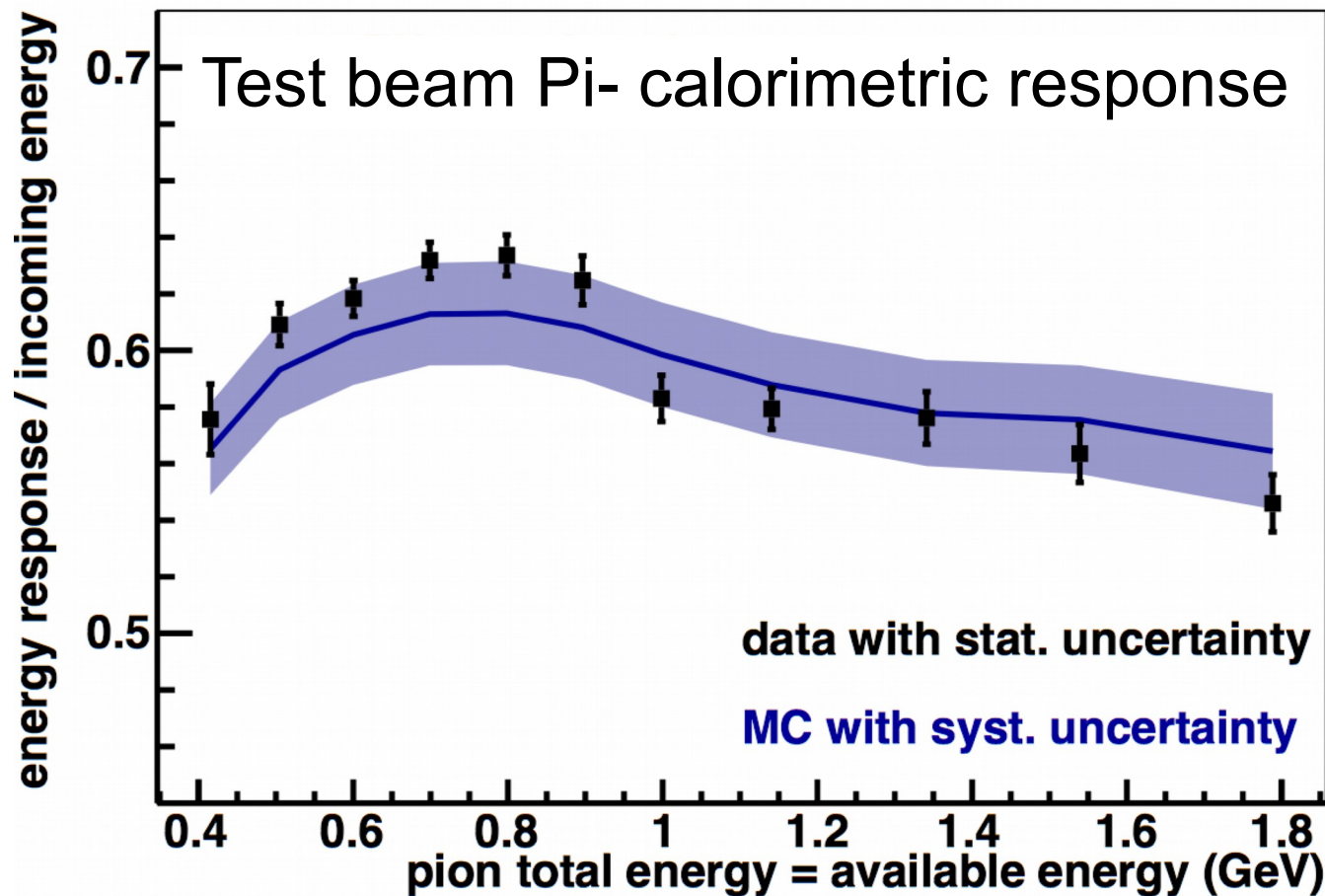
Ratios to passive target region for A-dependent analyses

Usually need μ in MINOS, $< \sim 20$ degrees, $E_{\nu} > 2$ GeV



Calorimetry constraints < 2 GeV from test beam data

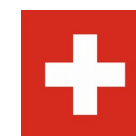
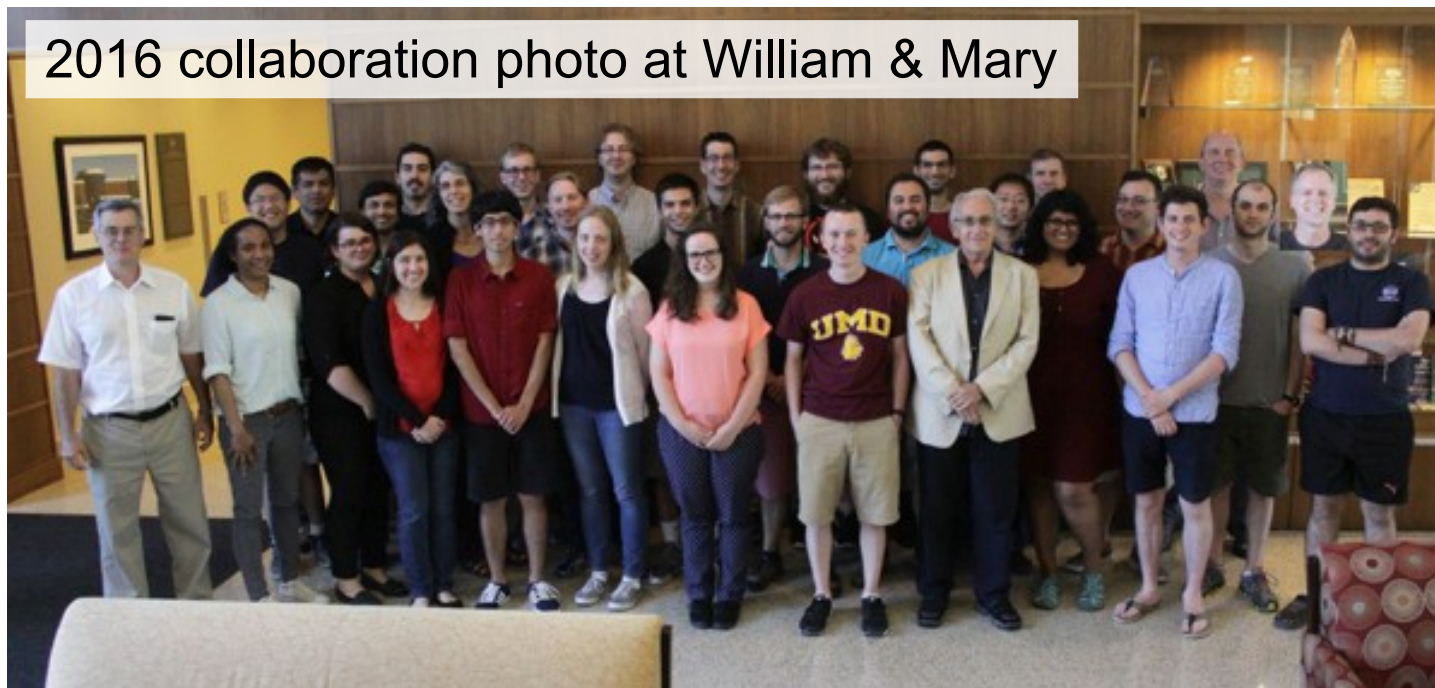
Constrains Geant4 and Detector calorimetric response
4% for protons, pions < 2 GeV and 3% electrons ~ 0.5 GeV



Resolutions are also well described
(also in-situ constraint from π^0 invariant mass peak)
and Birks' Law tune especially for stopping protons and PID₆

Most important elements of MINERvA experiment

2016 collaboration photo at William & Mary



Aligarh Muslim University

Centro Brasileiro de Pesquisas Fisicas

Fermilab

University of Florida

Universite de Geneva

Universidad de Guanajuato

Hampton University

Massachusetts College of Liberal Arts

University of Minnesota at Duluth

University of Mississippi

Otterbein University

Universidad Nacional de Ingenieria

Potificia Universidad Catolica del Peru

University of Pennsylvania

University of Pittsburgh

University of Rochester

Rutgers, the State University of New Jersey

Universidad Tecnica Federico Santa Maria

Tufts University

College of William and Mary

University of Wroclaw

Ingredients to the data and interpretation

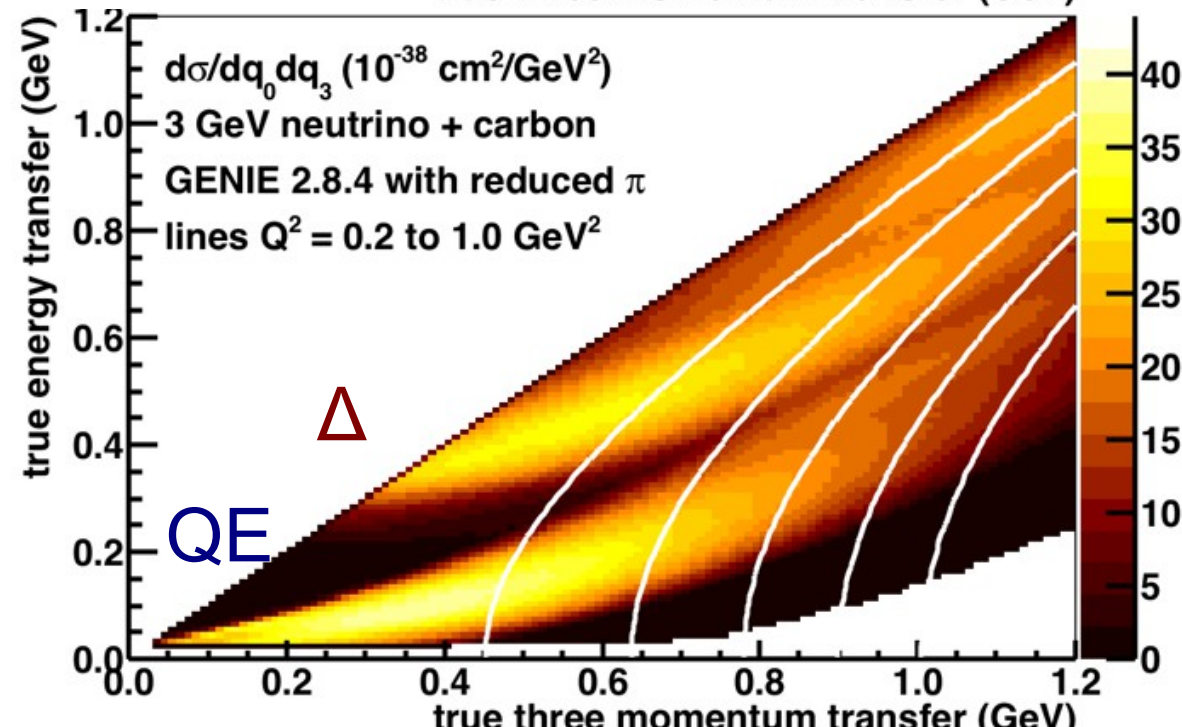
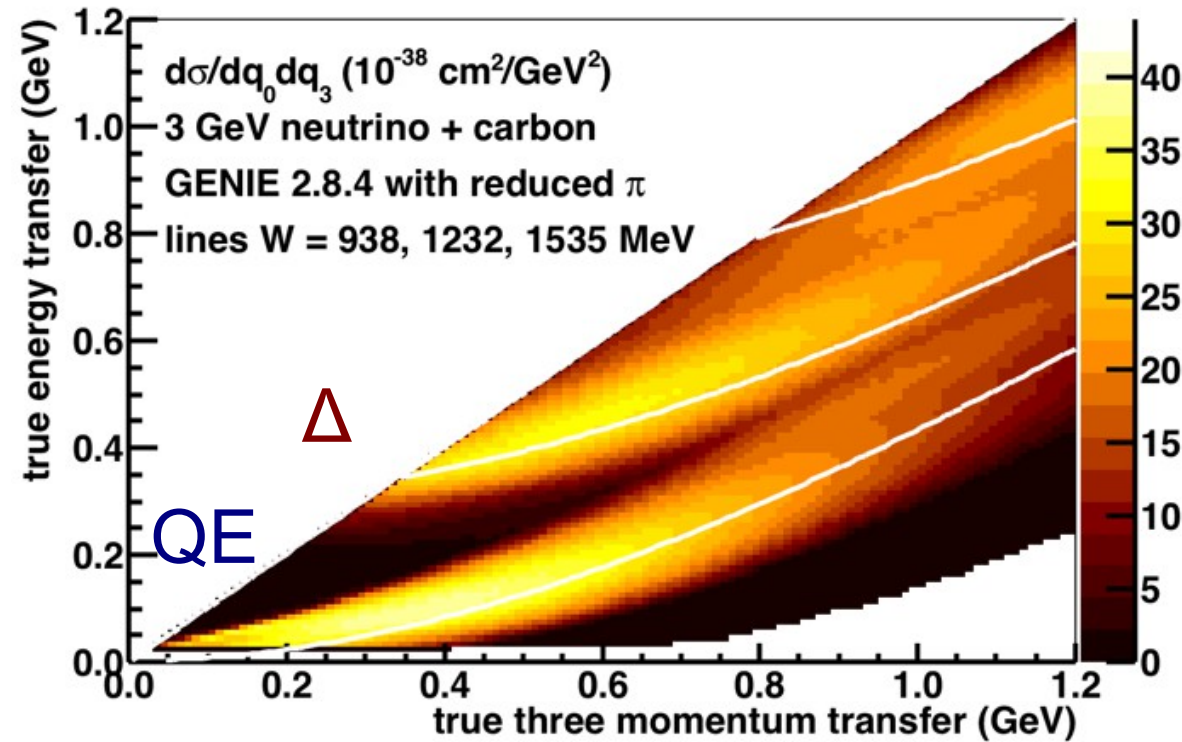
Kinematics choices Q^2 & W vs. q_0 and q_3

Reconstructed kinematics technical slides
available energy and energy transfer
calorimetric vs. QE hypothesis

What keeps oscillation analyzers up at night
calorimetric vs. QE hypothesis

Two multi-nucleon model details central to the story
RPA screening
two-particle knockout “2p2h” reactions

Kinematics: definitions and reconstruction

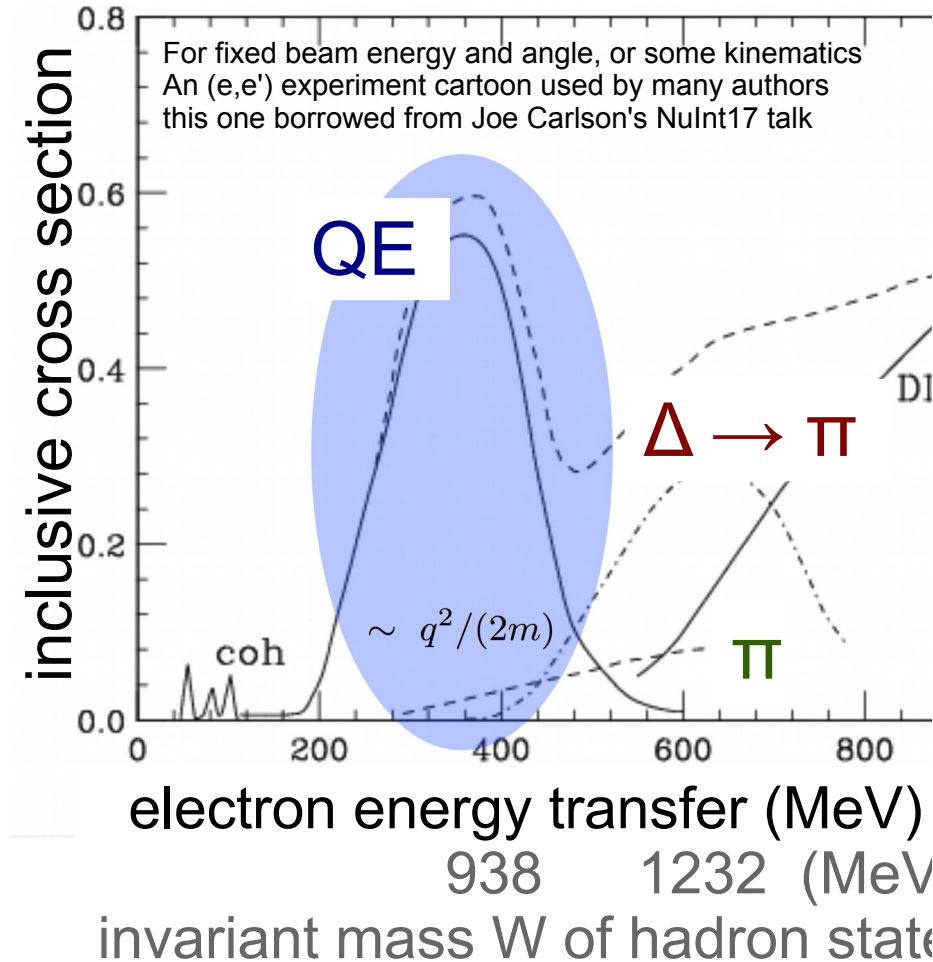
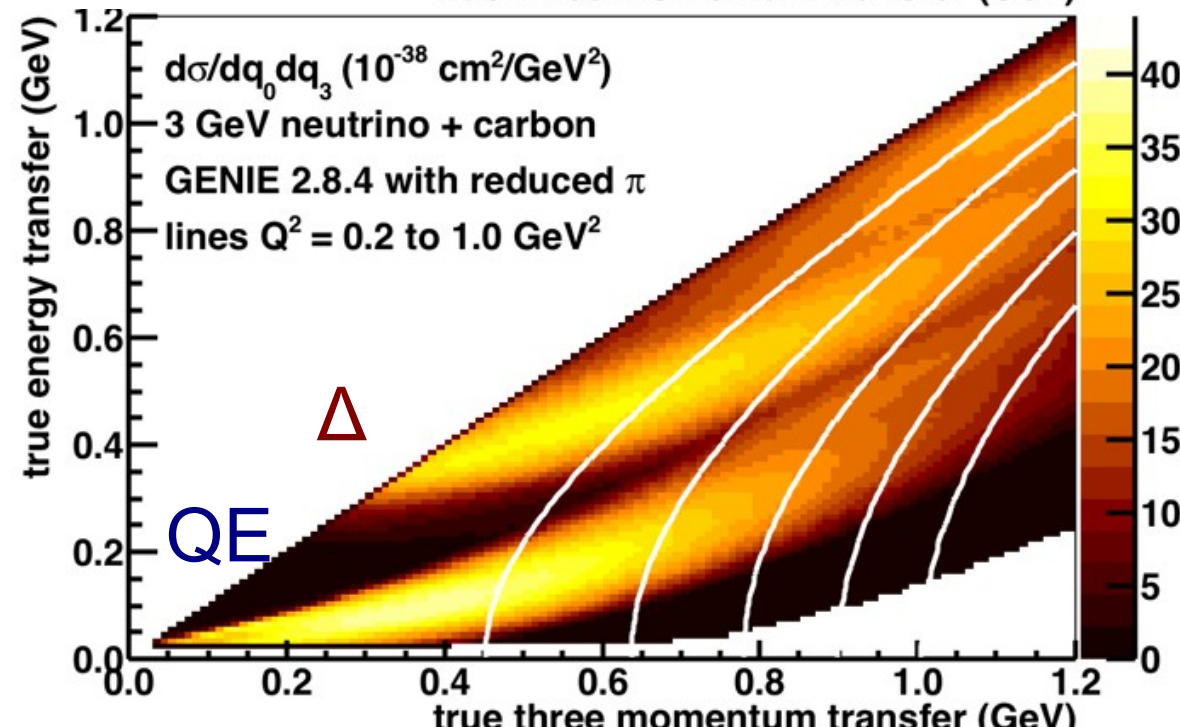
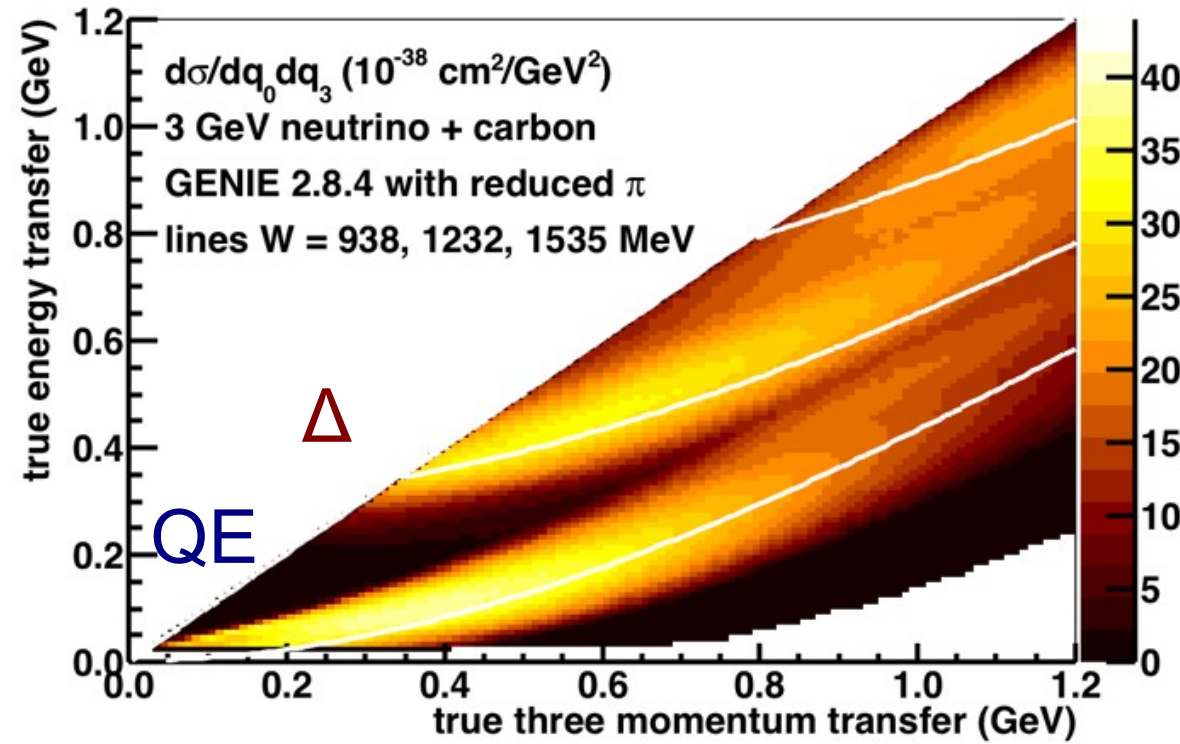


(Semi-)inclusive
ignore most details
of final hadron state.
pick just two:
 Q^2 and W (or W^2)
good for single nucleon

shown here
 q_0 and q_3
(ω and $|q|$)
("nu" v and $|q|$)
nucleus rest frame
hadronic tensor

x_{Bj} and (y or Q^2)
Deeply inelastic
single quark

Kinematics: definitions and reconstruction



Technical slide: steps to calorimetric reconstruction

We do not start knowing the energy of the neutrino, only the direction.

Measure the energy E_μ and angle θ_μ of the outgoing muon.

Measure the detected energy attributed to hadrons E_{visible} .

A. turn E_{visible} into $E_{\text{available}}$ using **detector** MC, discounts neutrons
 $E_{\text{available}}$ = Proton KE, π^\pm KE, π^0 , e, γ energy (plus heavier particles)
little neutrino model dependence (some anti-nu model dependence)

B. Use MC and correct to energy transfer q_0 ($= E_{\text{had}} = \nu = \omega$)
(unbiased, but correction has some dependence on neutrino model)

C. Estimated neutrino energy $E_\nu = E_\mu + q_0$

D. Estimated four-momentum $Q^2 = 2 E_\nu (E_\mu - p_\mu \cos \theta_\mu) - M_\mu^2$

E. Estimated momentum transfer $q_3 = \text{Sqrt}(Q^2 + q_0^2)$

F. Estimated experimenter's $W^2 = M_n^2 + 2 M_n q_0 - Q^2$

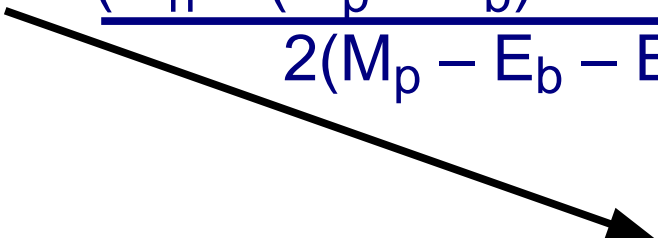
Technical slide: steps to QE hypothesis reconstruction

We do not start knowing the energy of the neutrino, only the direction.

Measure the energy E_μ and angle θ_μ of the outgoing muon.

If there is one tracked proton in the event, measure its energy and angle

Conservation of energy and momentum for two-body reaction gives only two, more limited, but not more simple, quantities

$$C. \quad E_v^{QE} = \frac{(M_n - (M_p - E_b)^2 + 2(M_p - E_b)E_\mu - M_\mu^2)}{2(M_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$


$$D. \quad \text{Estimated four-momentum } (Q^2)^{QE} = 2 E_v^{QE} (E_\mu - p_\mu \cos \theta_\mu) - M_\mu^2$$

Also haven't used hadronic information here, so still could.

Plus estimated four-momentum from proton only, shown later slide (is really just KE proton with a linear, slope+intercept transform)

No sense in estimating W for QE hypothesis its 938 MeV

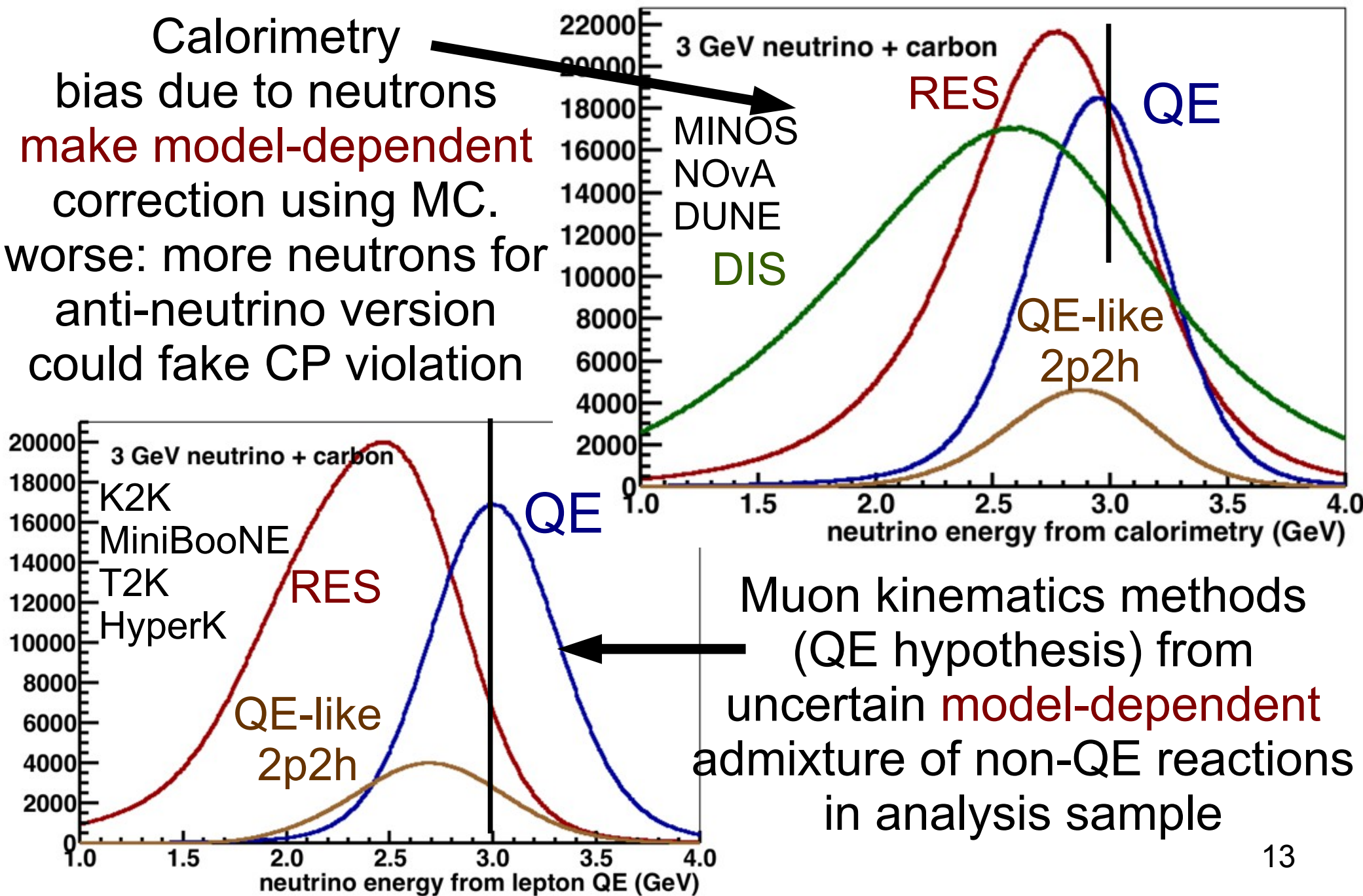
Note, mono-energetic electron beam experiments (JLAB, SLAC, others) don't get stuck, they always know the electron initial energy and direction.¹²

Methods to get wrong neutrino energy for oscillations

Ev bias is sorta-bad, **unmodeled Ev bias is very,very bad**

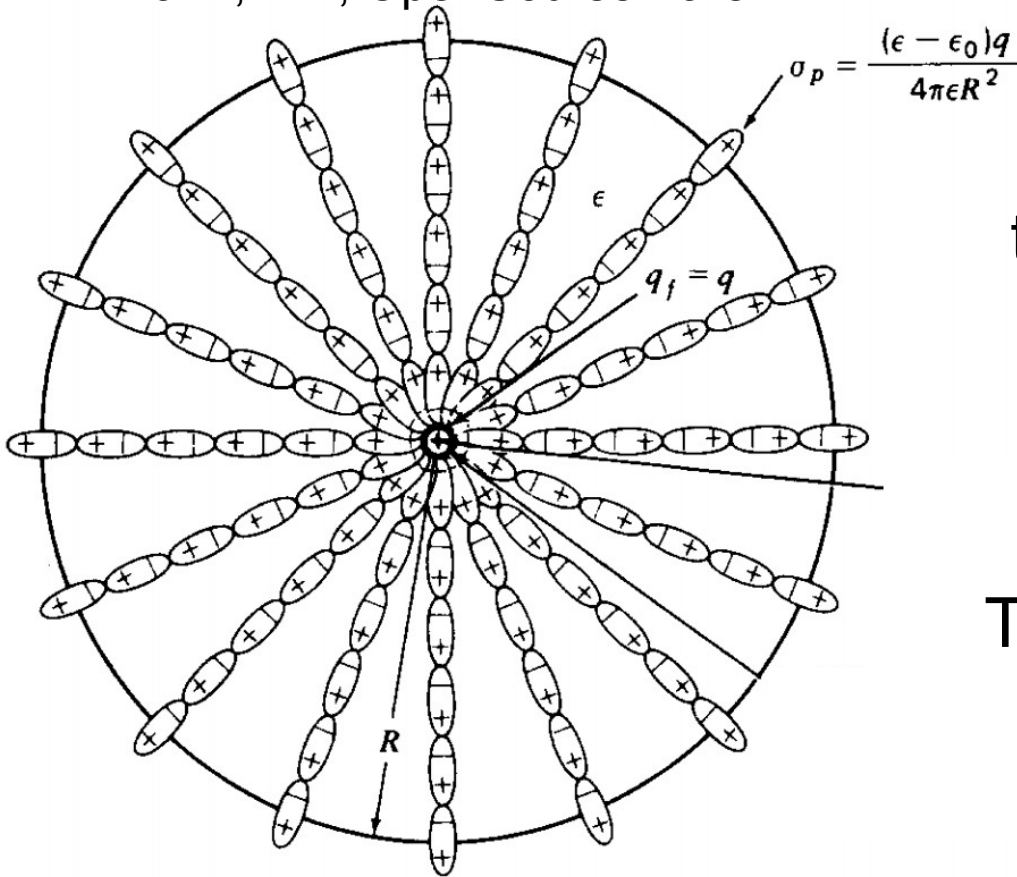
Calorimetry

bias due to neutrons
make model-dependent
correction using MC.
worse: more neutrons for
anti-neutrino version
could fake CP violation



Polarization screening effect (“RPA calculation”)

M. Zahn, MIT, OpenCourseWare



We learn in classical E&M
(e.g. Ch. 4 of Griffiths)

to apply Gauss' Law for a sphere
to get the E field from point charge
Polarization of a dielectric medium
(bound surface charge on inside)
“screens” and reduces the field.

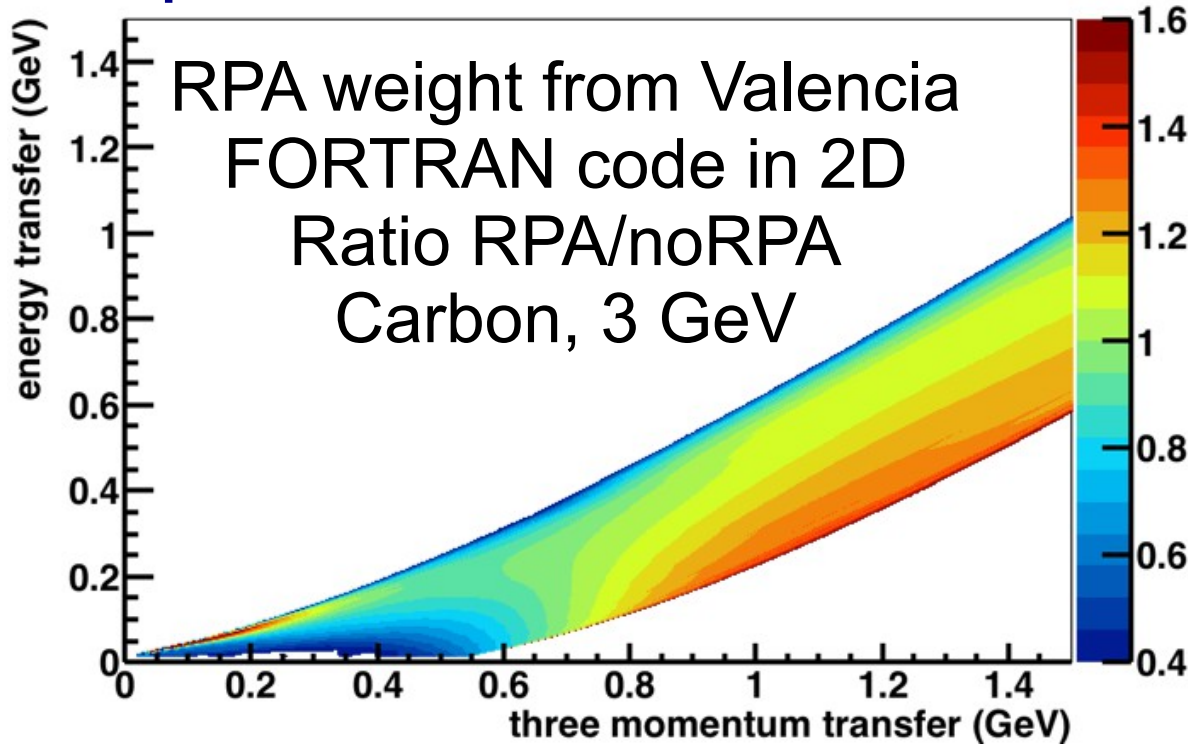
The quantum “RPA-type” calculation
for electron gas or nuclear matter
gives long-range (whole medium)
nucleon-nucleon correlation.

Figure 3-6 The electric field due to a point charge within a dielectric sphere is less than the free space field because of the partial neutralization of the point charge by the accumulation of dipole ends of opposite charge. The total polarization charge on the

Classic references
Bohm, Pines, 1952
also Walecka 1971

**Net effect is the nucleon at $Q^2 = 0$ limit is screened
looks like only 60% of a nucleon**

Implementation of Valencia RPA effect for Carbon



Designed to apply to a
Fermi-gas model.
When applied to a
a mean-field nucleus
has smaller relative effect
total (mean field + RPA)
is similar in magnitude
(Nieves, Sobczyk and Jachowicz)

Valencia RPA weight and model error band

Nieves, Amaro, Valverde PRC 70 (2004) 055503

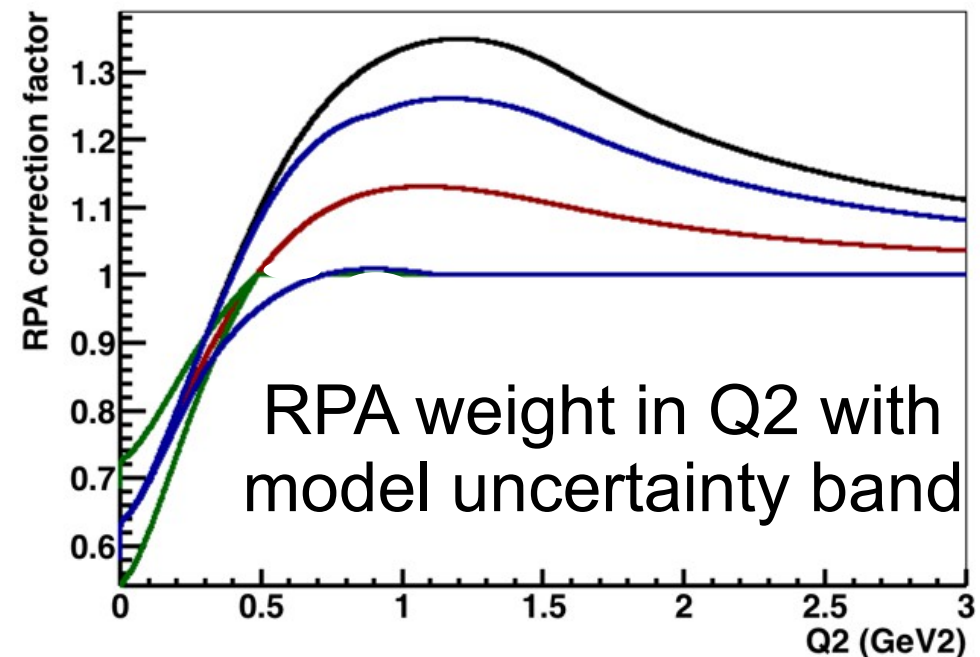
Valverde, Amaro, Nieves PLB 638 (2006) 325

with unpub. followup by F. Sanchez

plus uncertainty from

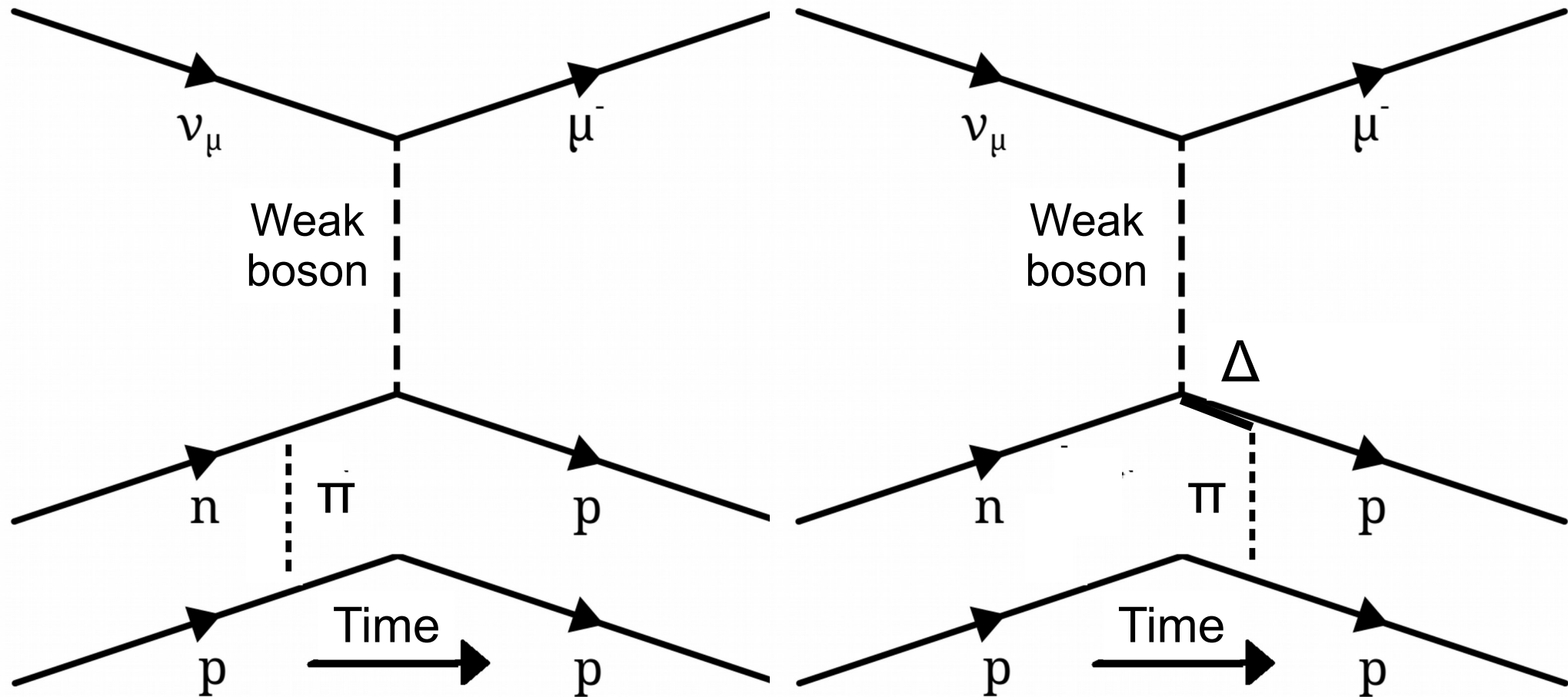
benchmarking to muon capture

and implementation R.G., arXiv:1705.02932



“2p2h” mixed in with the QE and the $\Delta(1232)$?

Reaction involved two nucleons, knocking out both



interaction with two particles in the process of pion exchange
both are knocked out, creating two holes in the nucleus (2p2h)

Not a single particle, more degrees of freedom,
can appear to have W from QE (0.938) to Δ (1.232) ¹⁶

First example: inclusive cross section $q_3 < 0.8 \text{ GeV}$

Historically a more recent development for MINERvA

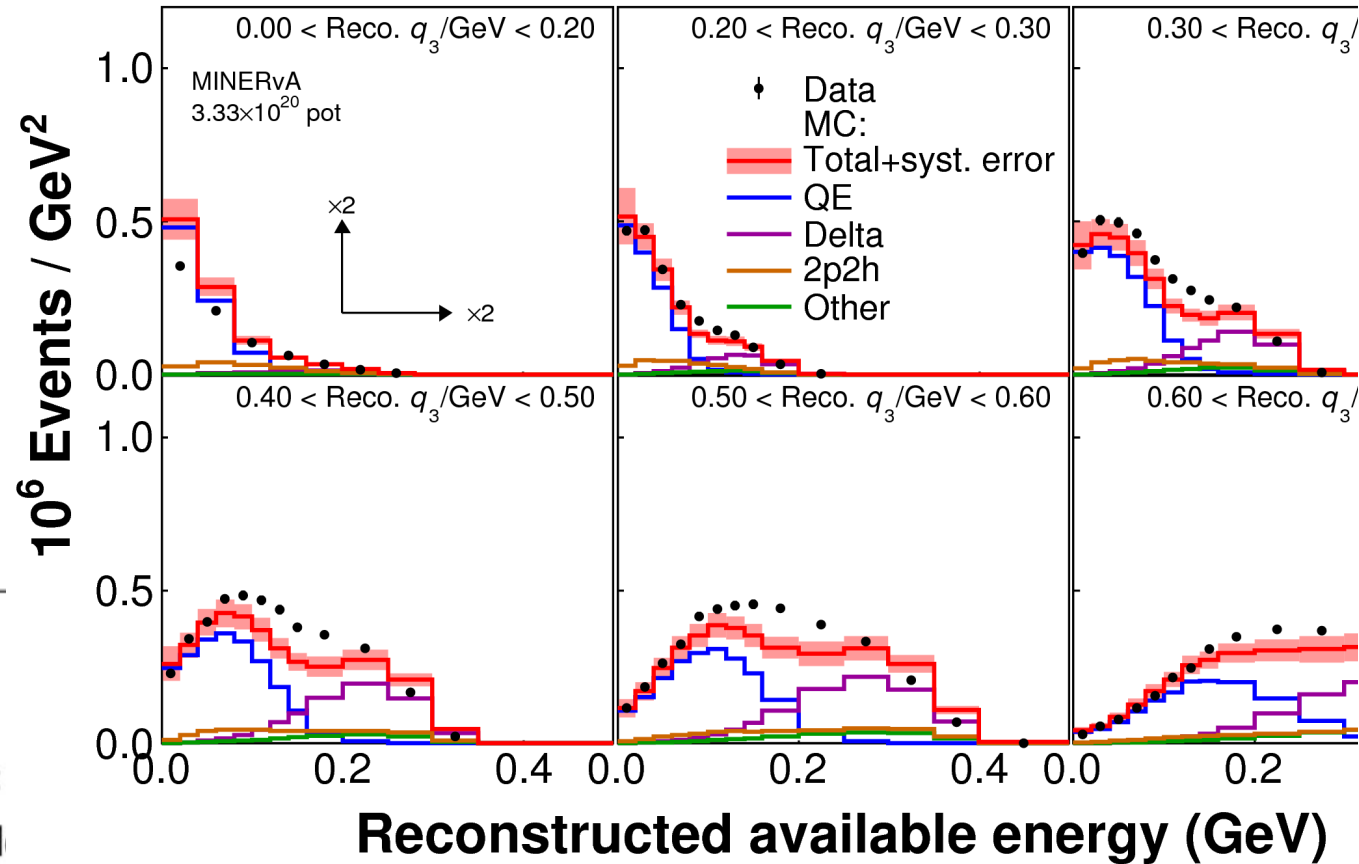
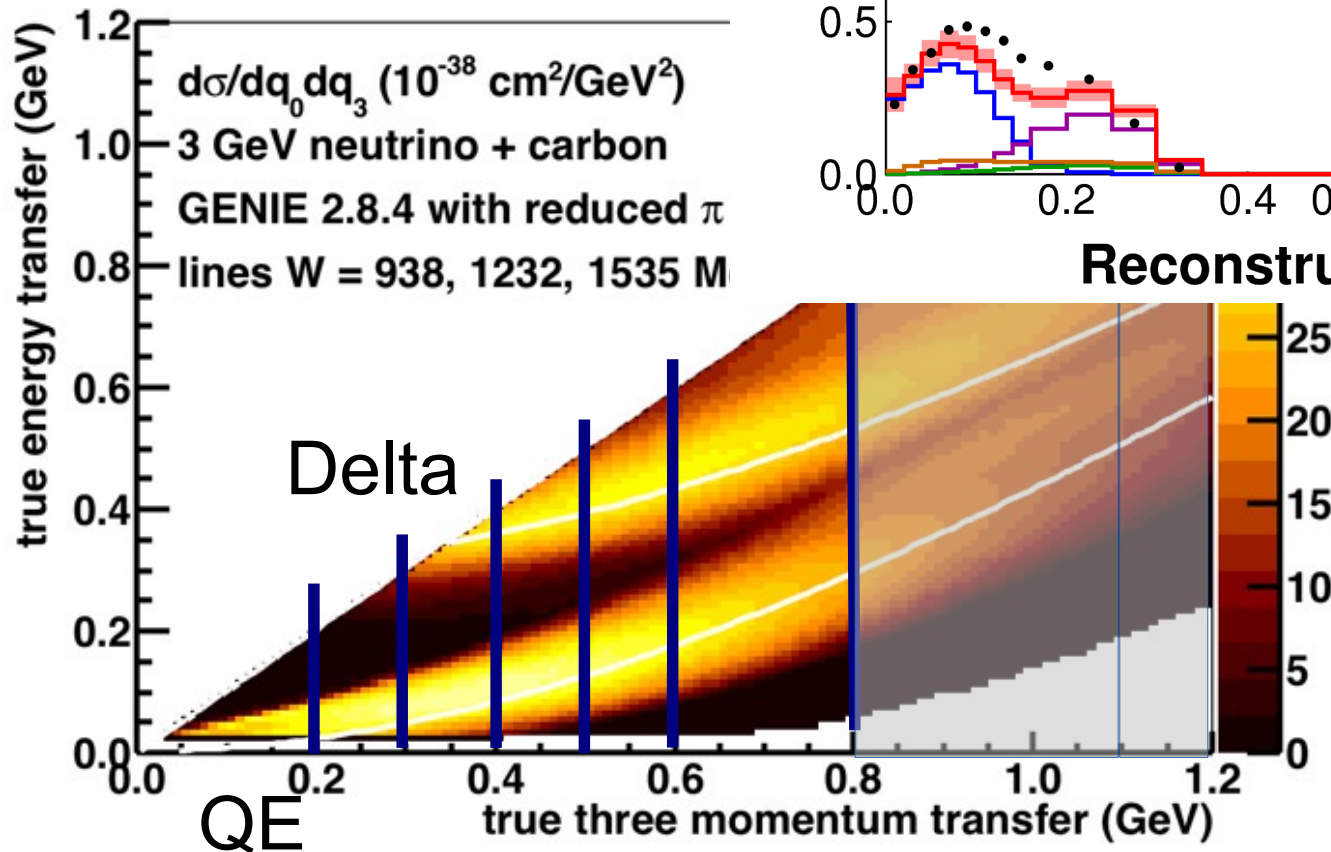
but for this talk, will be used to
unify the overall story

because we can
inspect the QE and the Delta together

then later look at what we get after selections
for events with and without pions

Analysis goal: (e,e')-like detail in six slices of q_3

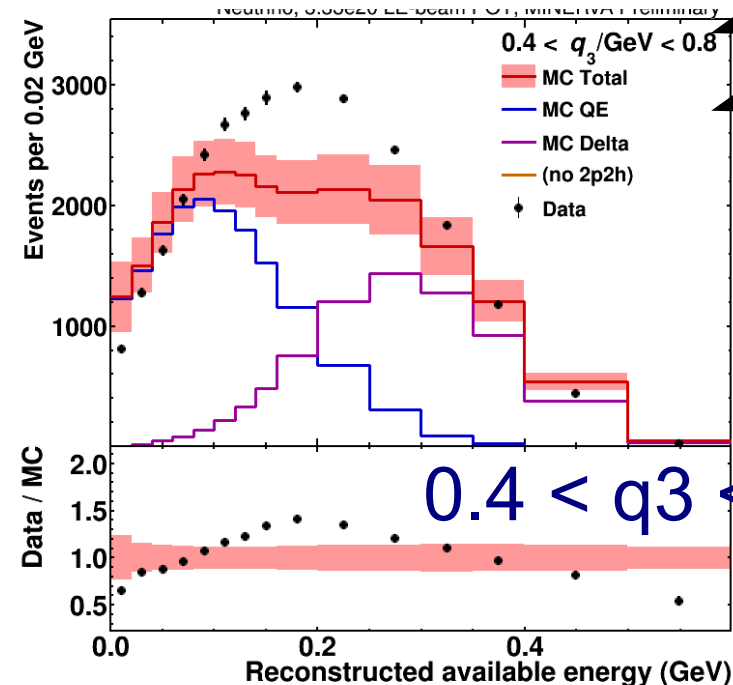
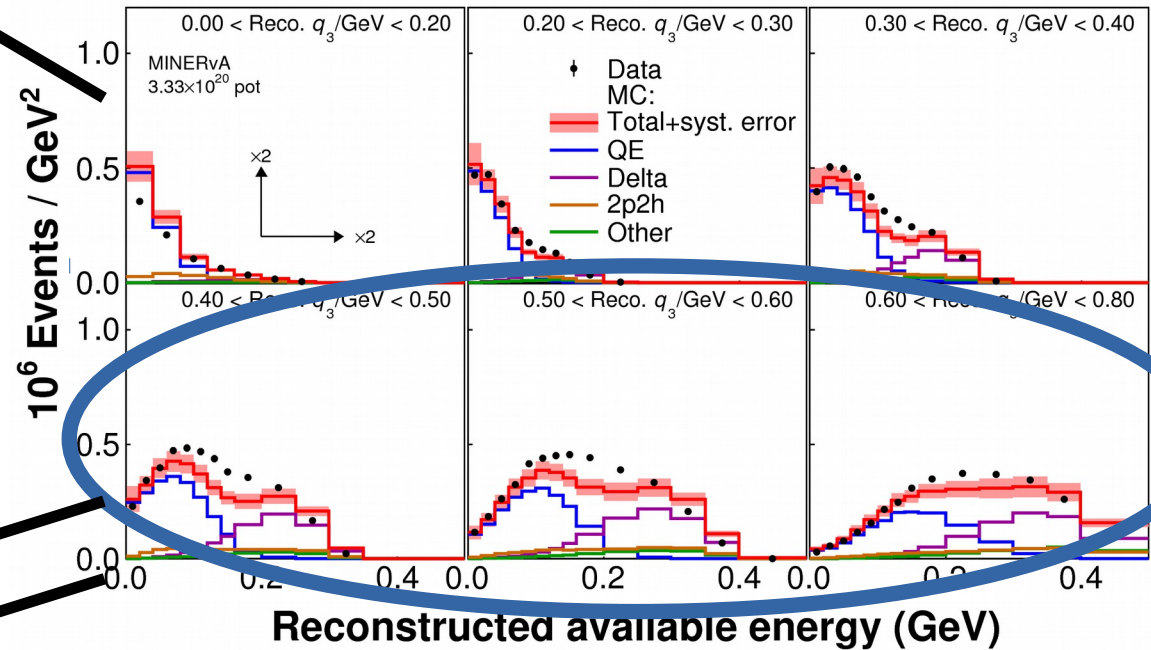
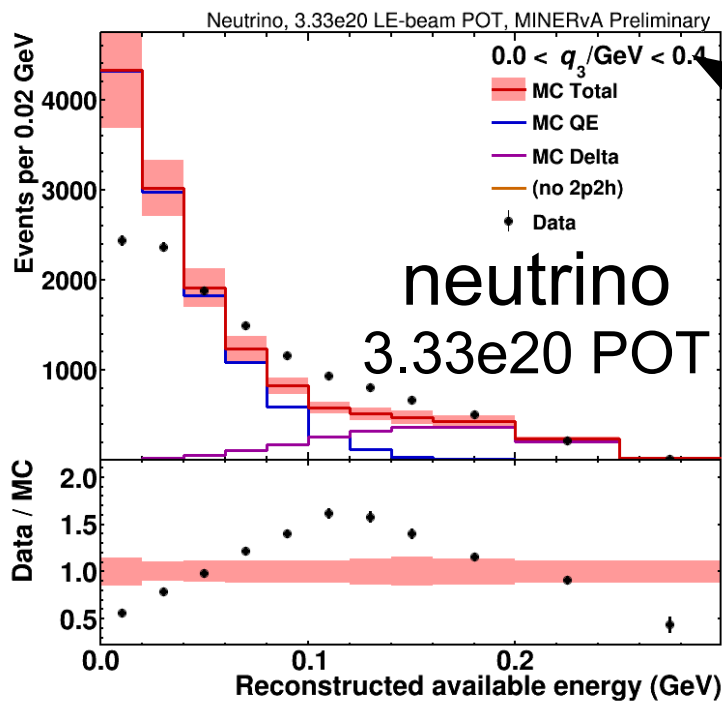
but use something
more observable,
detector-centric,
less model dependent
Eavail instead of
true energy transfer



This cross section
includes all GENIE
nu+C processes,
except 2p2h



Reduce to just two slices of q_3



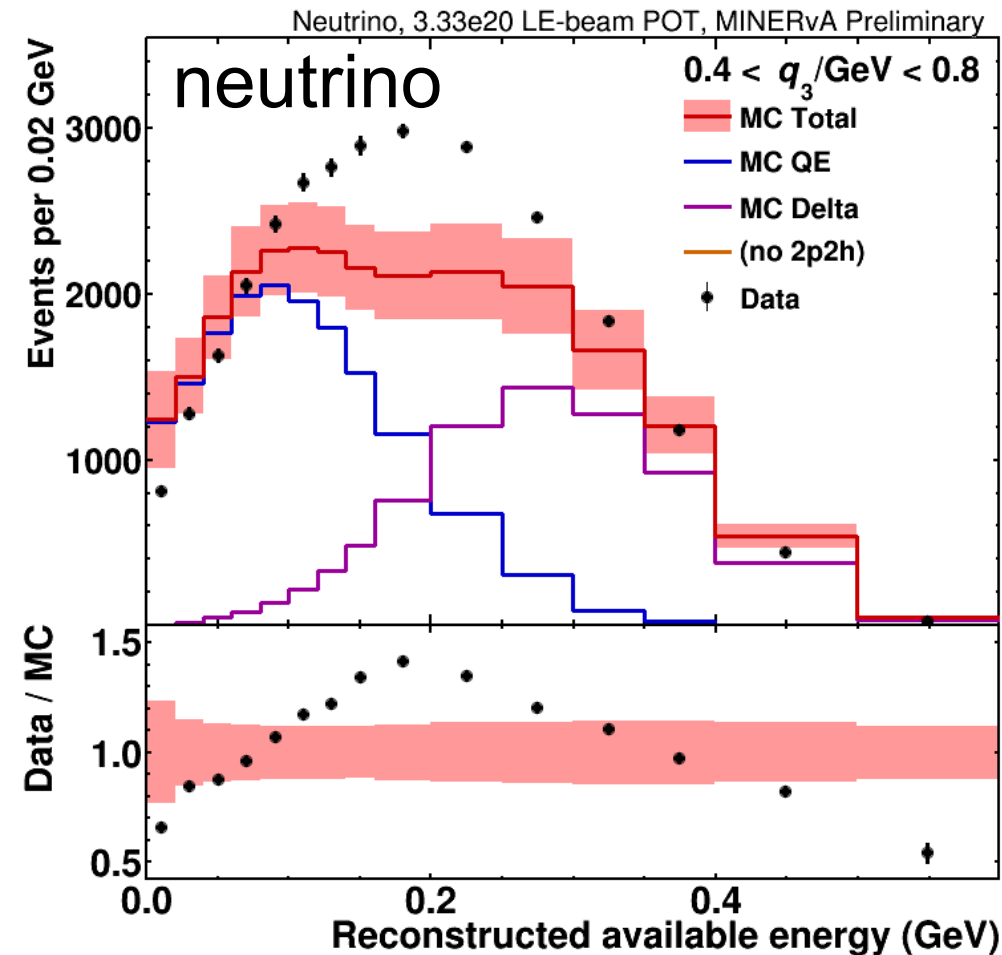
Reco data and chisquares
(and unfolded cross sections)
are from distributions made
with resolution-driven six bins
condensed into just two plots
good for physics interpretation

Rodrigues, Demgen, Miltenberger
et al. [MINERvA] PRL 116 071802

Can put one or two on a slide
nice and big, flipbook models

$0.4 < q_3 < 0.8$ GeV, GENIE + minor pion adjustment

X2 = 407 for 21 bins



Flipbook order
GENIE, no RPA, no 2p2h
yes RPA, no 2p2h
yes RPA, yes 2p2h
yes RPA, yes “tuned” 2p2h

fun fact! stat errors will often
be too small to see!

Chisquare with systematics is
three q_3 panels on prev. slide

What to look for:

Does the ratio look more flat? Closer to 1.0 + error band?

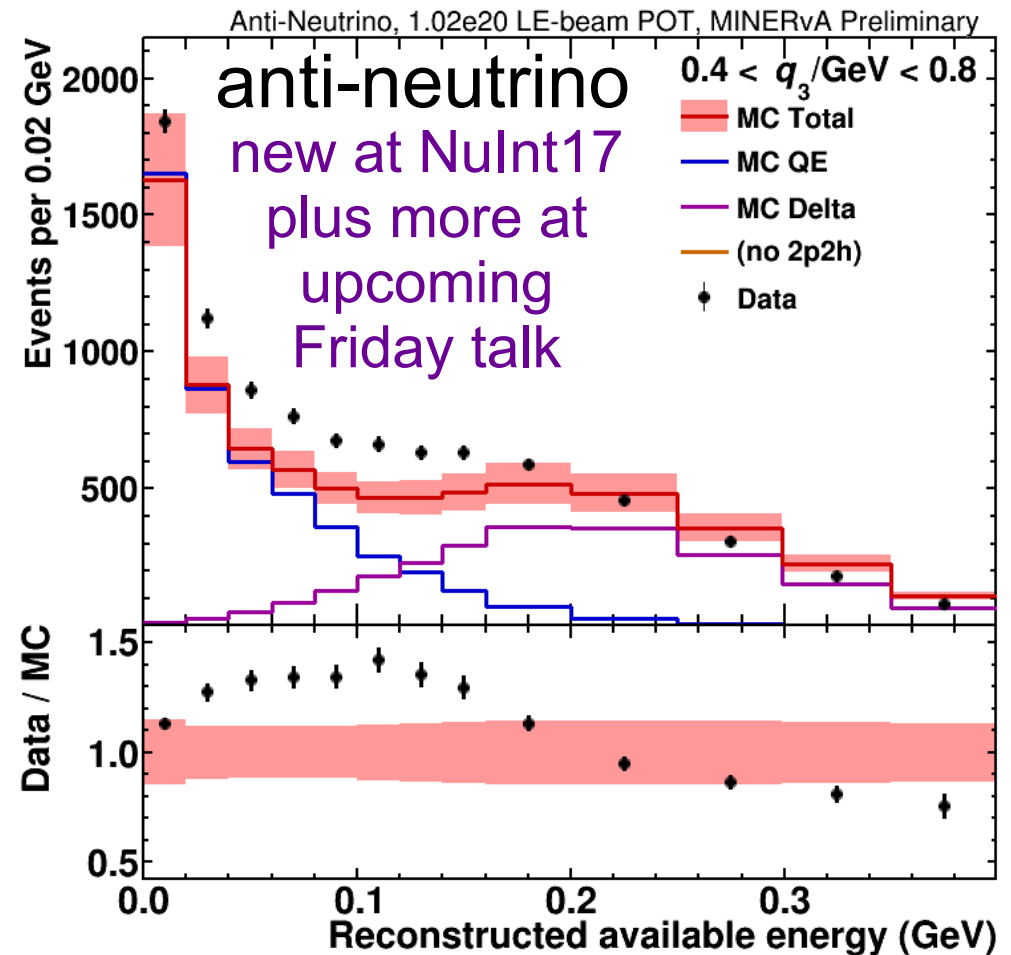
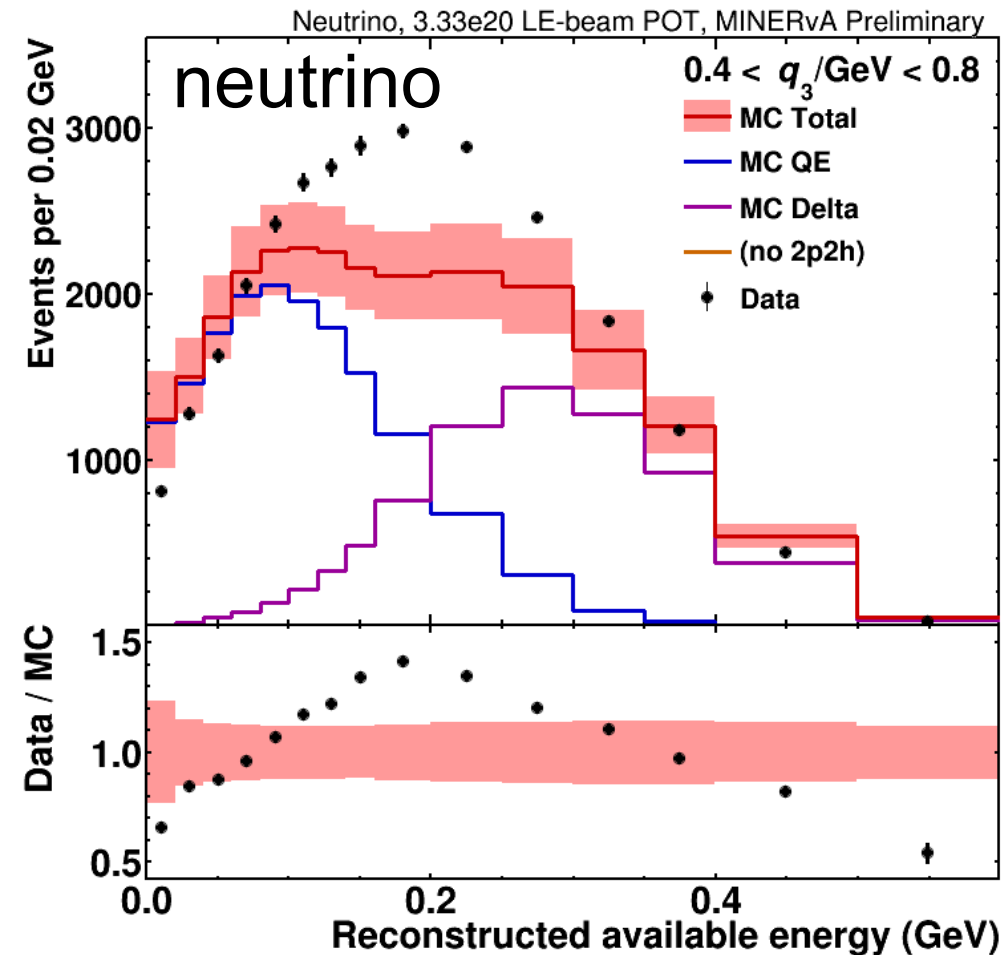
Is the chisquare better? Can a different model do better?

Did the model change affect QE, Dip, or Delta region?

GENIE, pion base, no RPA, no 2p2h

X2 = 277 for 40 bins

X2 = 172 for 37 bins



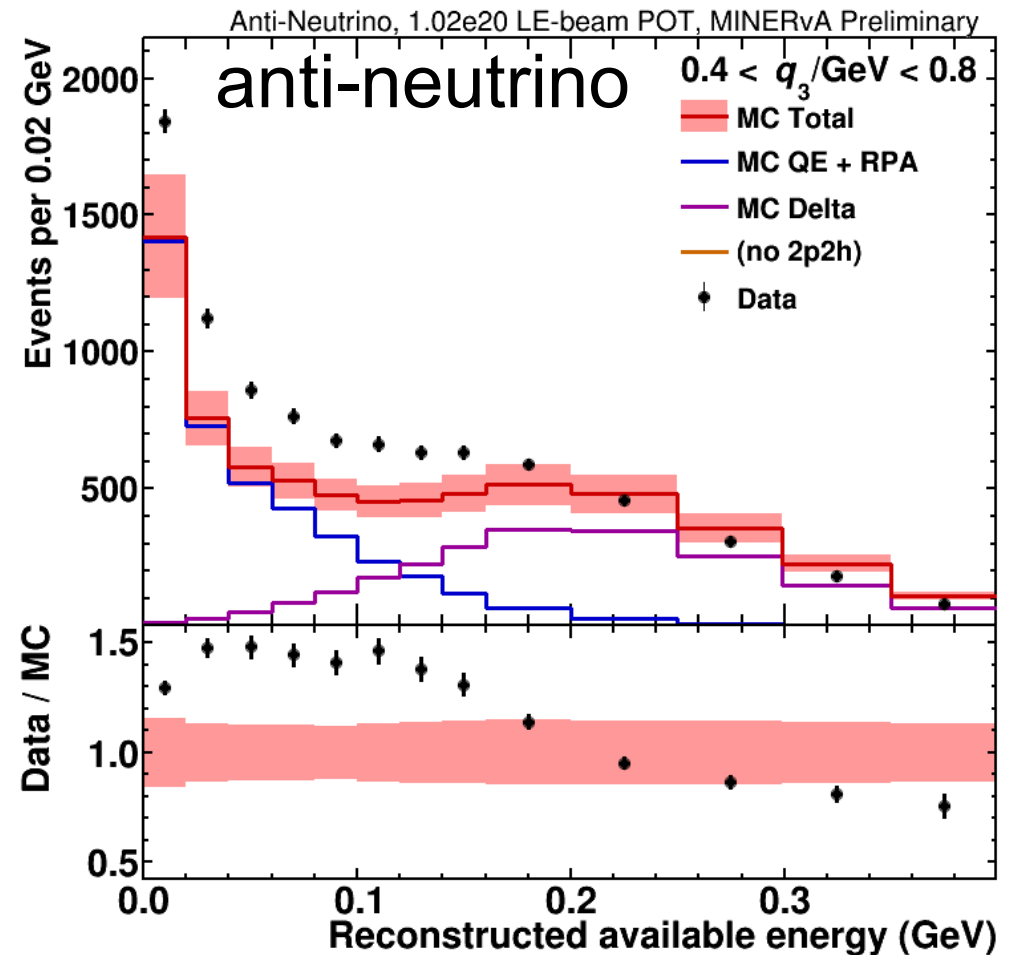
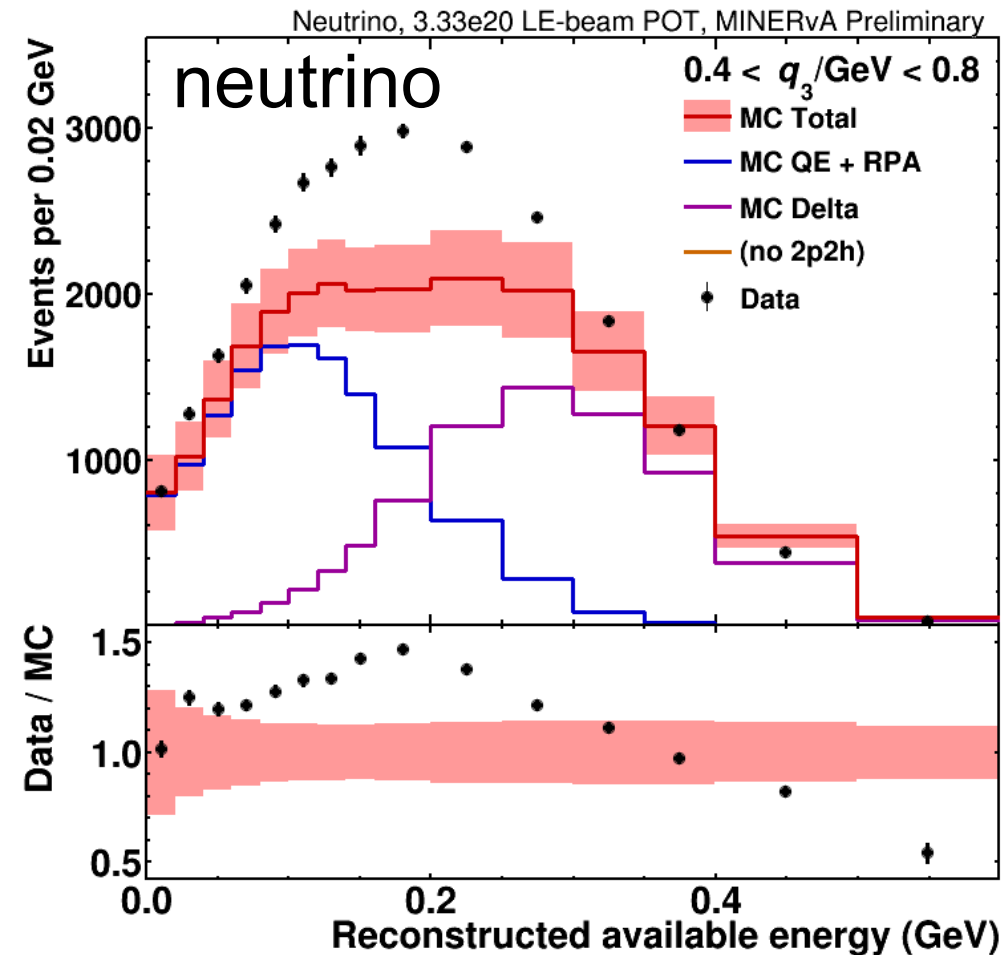
Characteristic MC underprediction in the dip region

The neutron final states even more obviously
cause high population in the first anti-neutrino bin.
discrepancies have same structure as at lower q_3

GENIE, pion base, RPA, no 2p2h

X2 = 247 for 40 bins

X2 = 131 for 37 bins



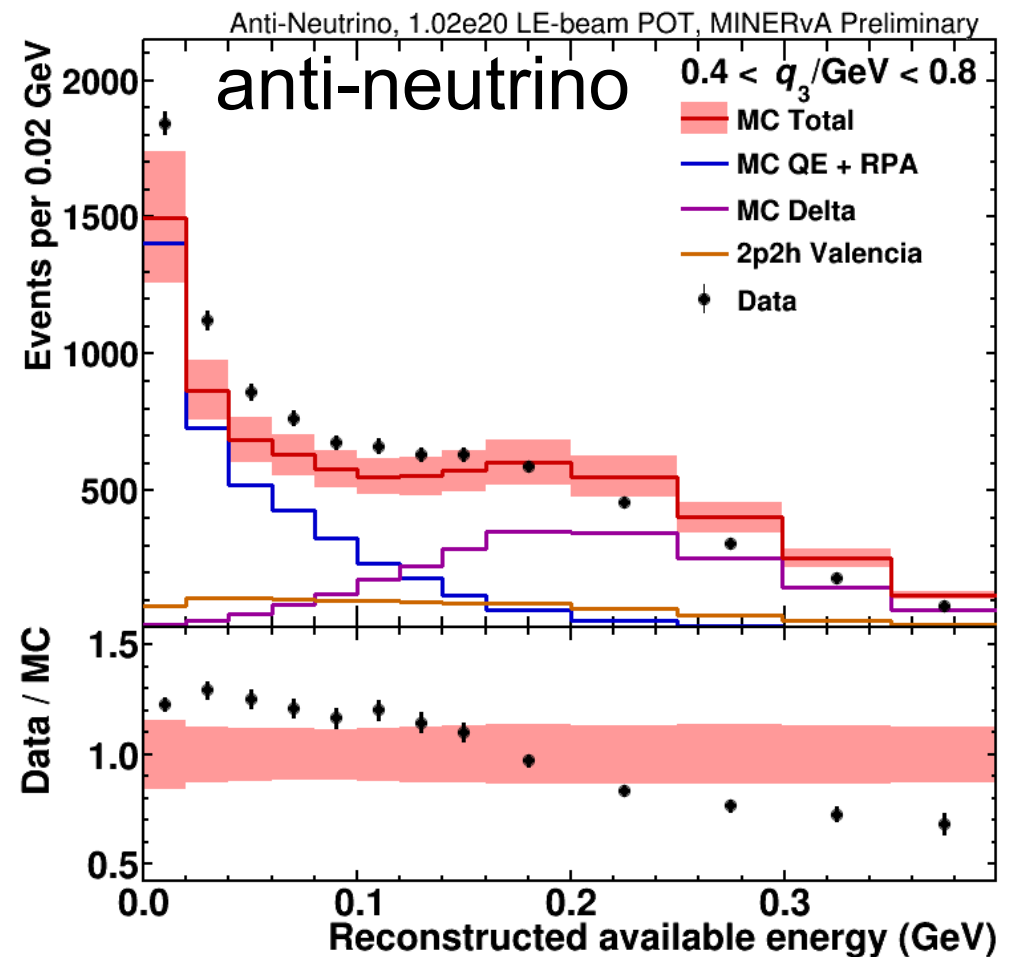
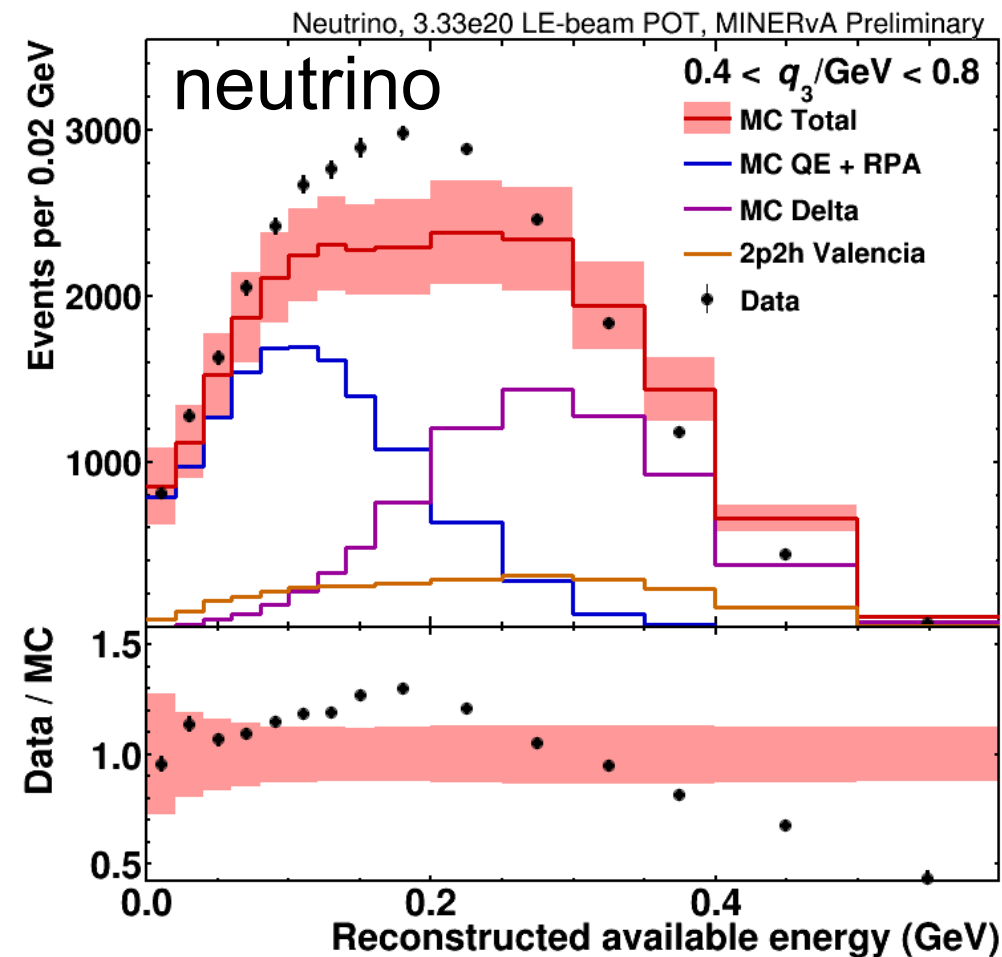
Add (updated) Valencia RPA weight
Nieves, Amaro, Valverde PRC 70 (2004) 055503
and **model error band**

Valverde, Amaro, Nieves PLB 638 (2006) 325 with unp. followup by F. Sanchez
plus muon capture uncertainty and implementation R. Gran, arXiv:1705.02932

GENIE, Pion base, RPA, Valencia 2p2h

X2 = 295 for 40 bins

X2 = 101 for 37 bins



Add Valencia 2p2h model, as previously published

Nieves, Ruiz Simo, Vicente Vacas PRC 83 (2011) 045501

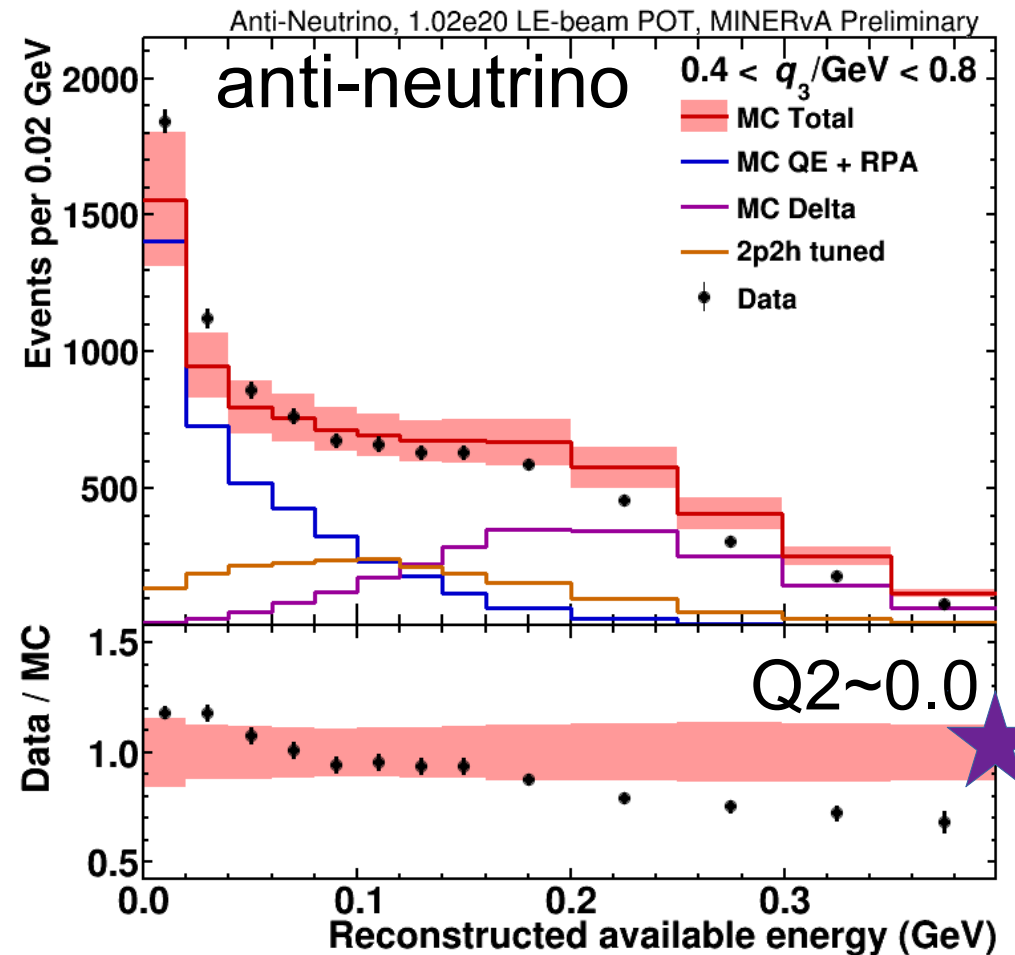
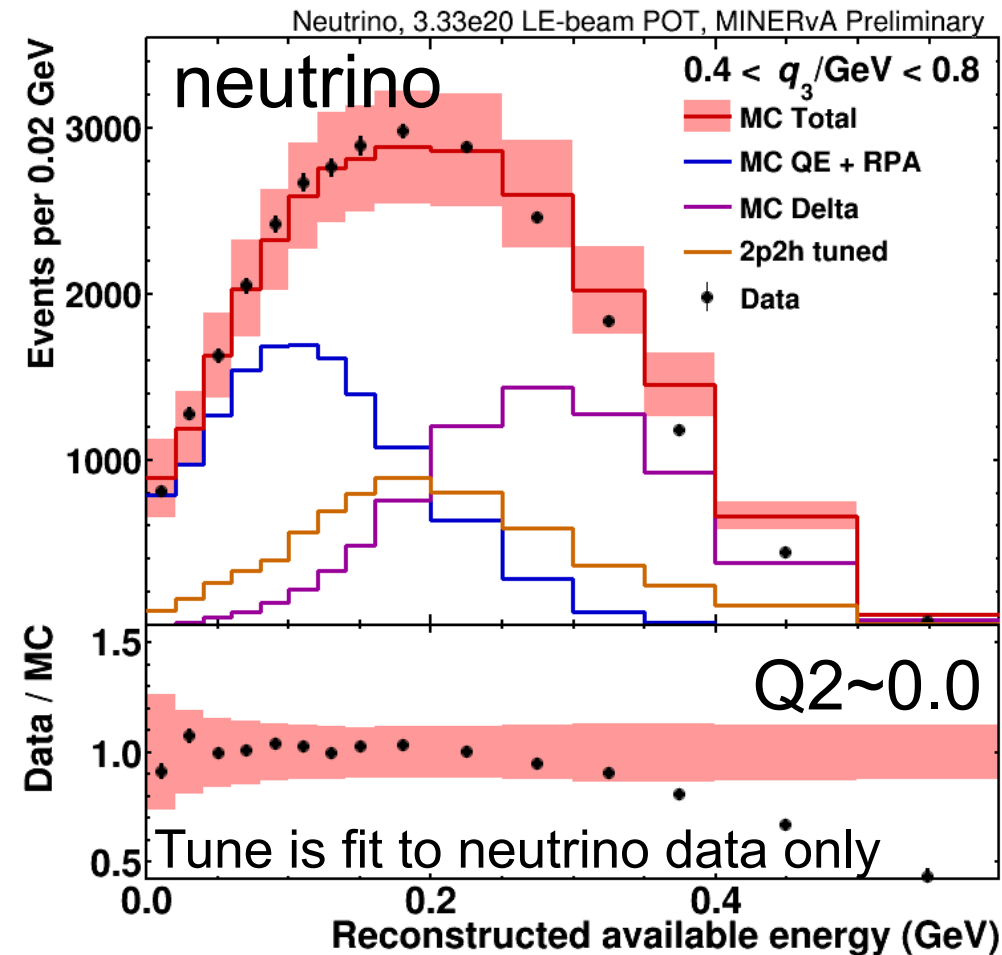
R.G., Nieves, Sanchez, Vicente Vacas PRD 88 (2013) 113007

Implemented in Genie 2.12.6 Schwehr, R.G., Cherdack, arXiv:1705.02932

GENIE, Pion base, RPA, 2017 Tuned 2p2h

X2 = 158 for 40 bins

X2 = 86 for 37 bins



weighting up the 2p2h events with a 2D Gaussian weight

this base tune designed to empirically “Fill in” the dip region

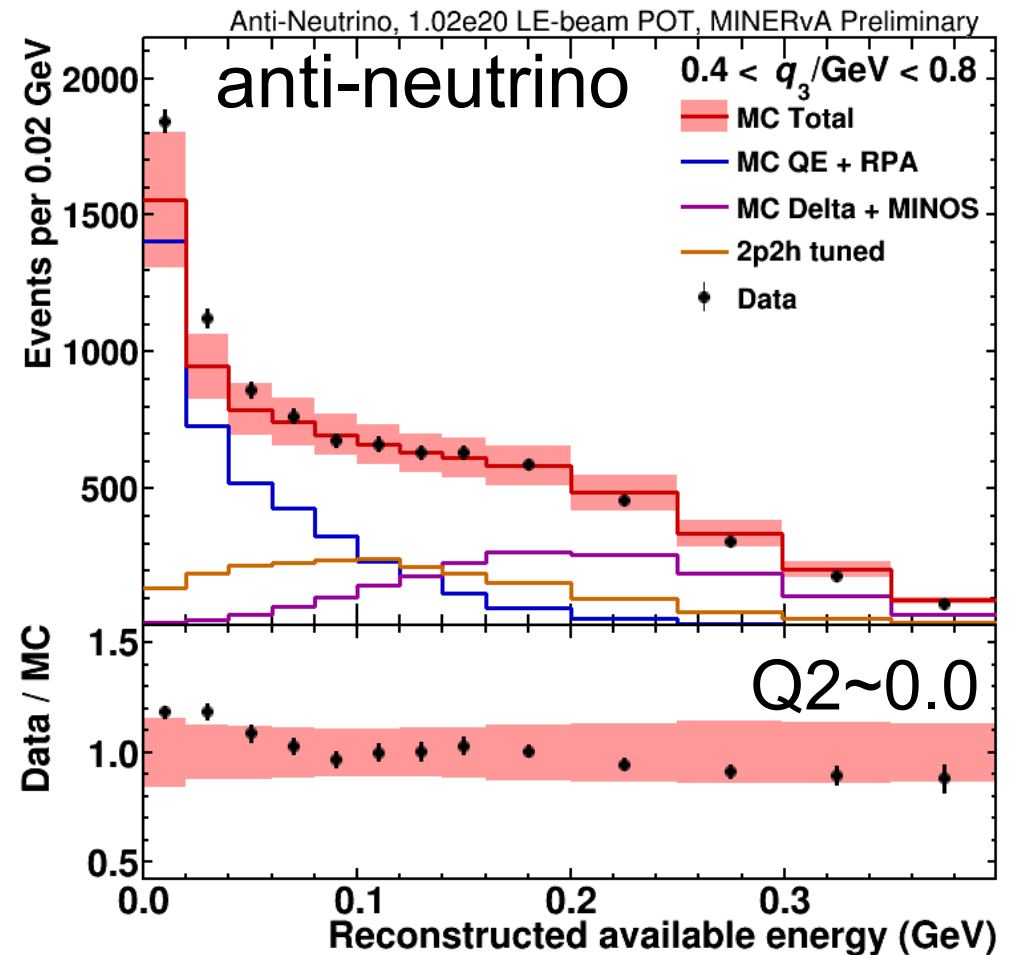
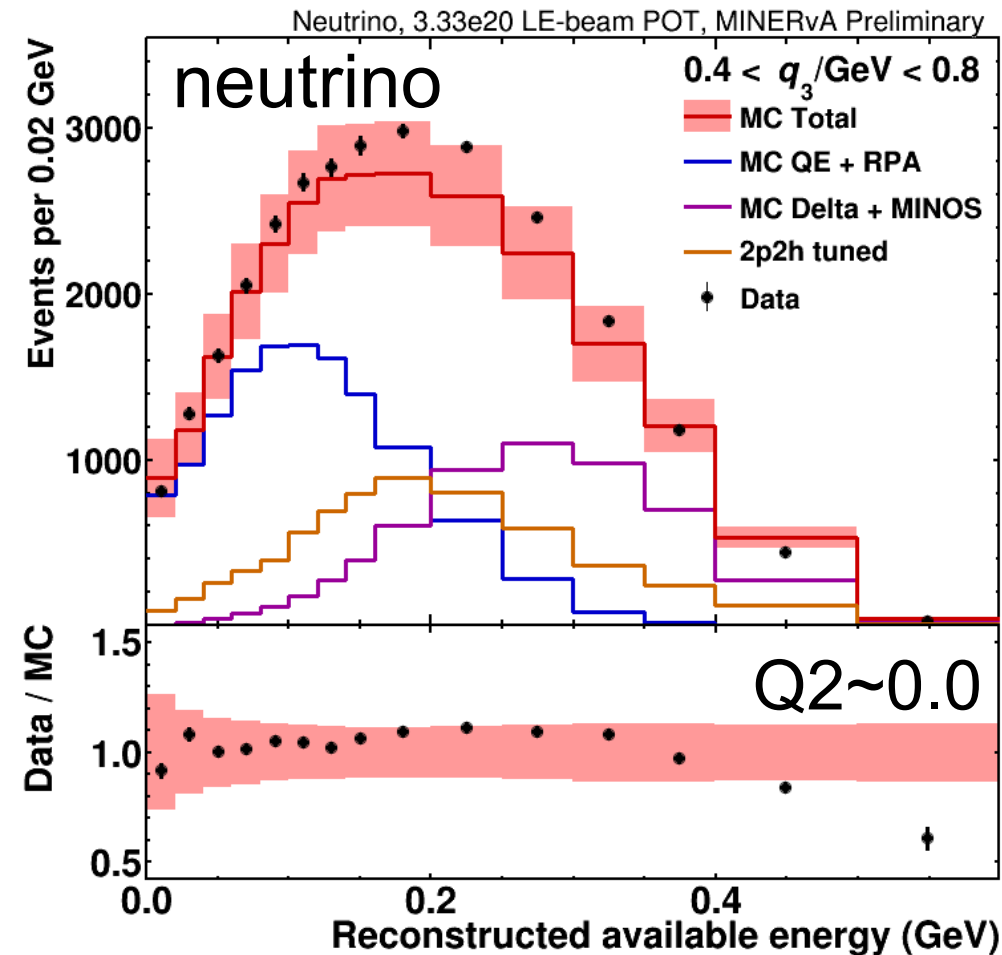
not whole kinematic range. Adds ~50% overall, but x2 in dip region

Improves left plot by construction, those parameters are applied to the anti-neutrino plot, which is also greatly improved!

GENIE, RPA, 2017 Tuned 2p2h, MINOS low-Q2 res

X2 = 144 for 40 bins

X2 = 59 for 19 bins



Option, add low Q2 suppression (RPA-like) to all GENIE resonances
prescription from Minos nu+Fe data PRD 91 (2015) 012005
Seen also in MiniBooNE, K2K, others...

? Pauli-blocking + RPA and/or SF-like effects but for resonances.
Improvement, but (not shown) goes too far for $q_3 < 0.4$ GeV ²⁵

Those model elements
described the event rate
AND the hadron spectrum
at the $\pm 10\%$ level
up to the Delta peak!

(despite radically different neutron content
in the anti-neutrino case.)

Same story for $0.0 < \text{reco } q3 < 0.4 \text{ GeV}$
details at NuInt17, in future talk

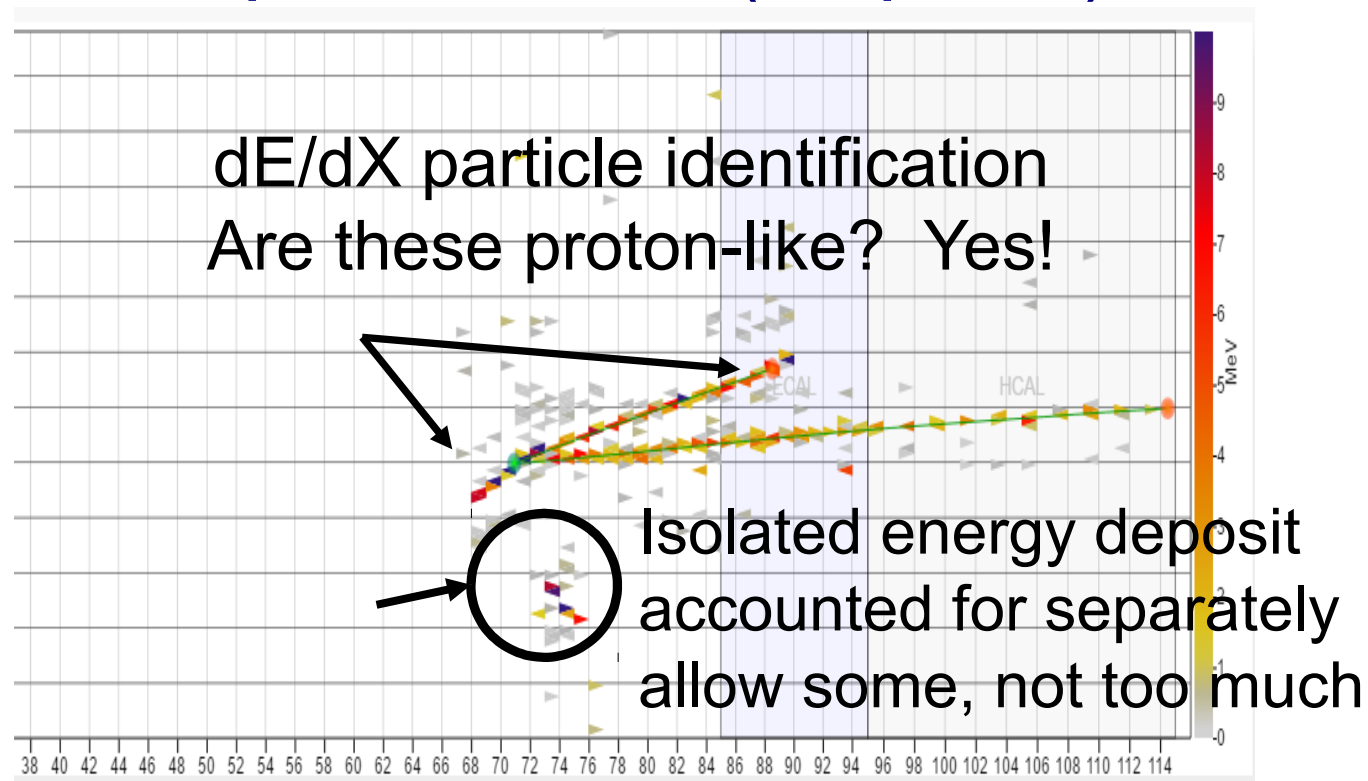
“MINERvA Tune v1” is RPA + 2p2h + extra 2p2h
(plus non-res pion and modified coherent pion
but NOT the optional MINOS resonance tune)

Second example: QE-like (no pions) subsample

Cheryl
Patrick
W&C
NuInt15

Dan
Ruterbories
W&C
NuInt17

2xPRD in
preparation



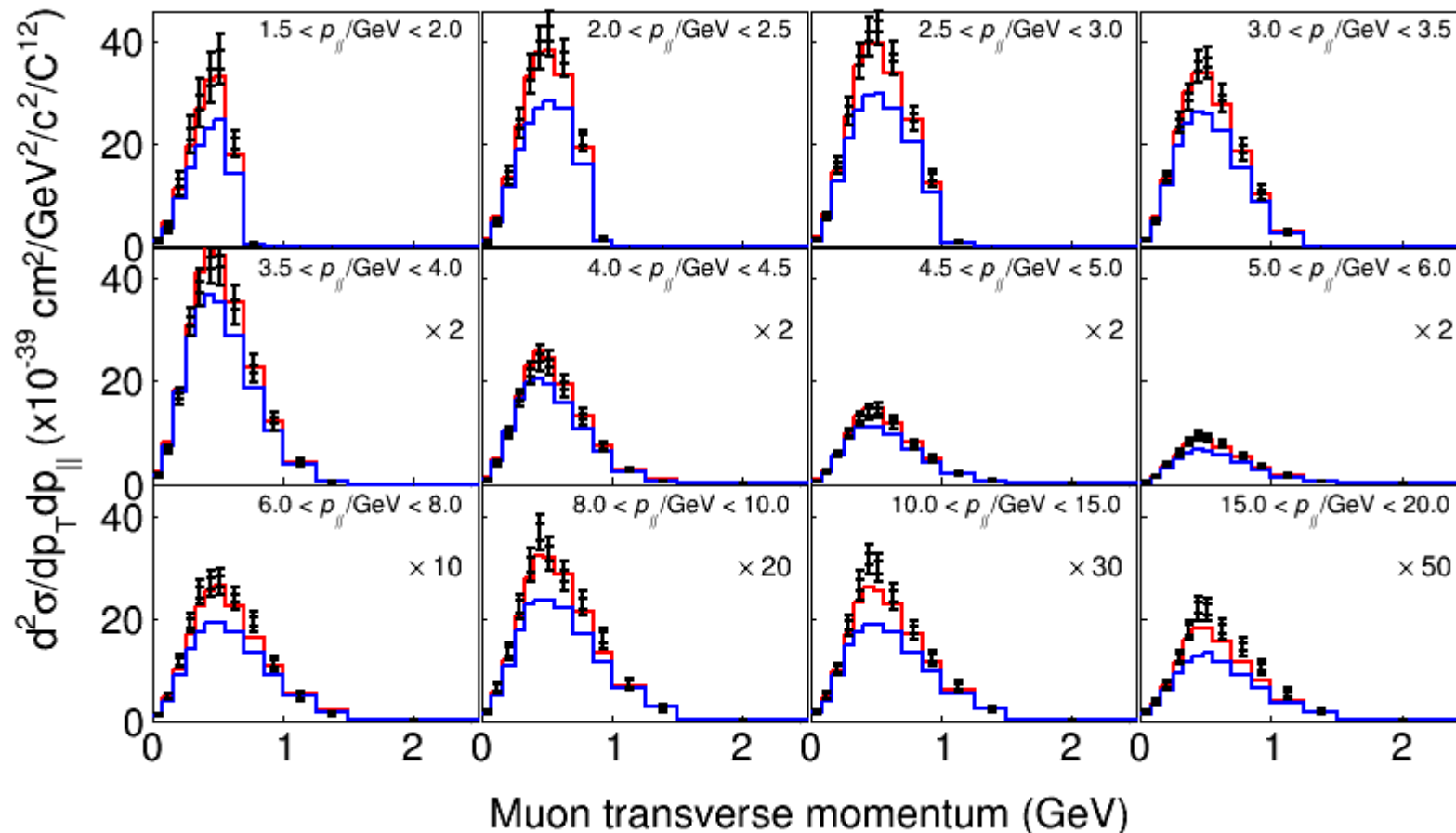
Keep events where all tracks are proton-like
reject events with non-proton-like tracks or Michel electrons
result is QE-like = 1 muon, N protons+neutrons, 0 pions

Highly efficient enriched true QE events as **signal**
should pass all 2p2h0pi events as **signal**
Delta-caused **signal** where pion did NOT exit nucleus via FSI
(and some true pion **background** due to mis-ID)

QE-like events (no pion) viewed from muon kinematics

Ruterbories, [MINERvA], in preparation

can use either muon (energy and angle) or ($p_{||}$ and p_{\perp})
is the detector observable that is historically easy for theory



GENIE
2.8.4

MINERvA
Tune v1
is better

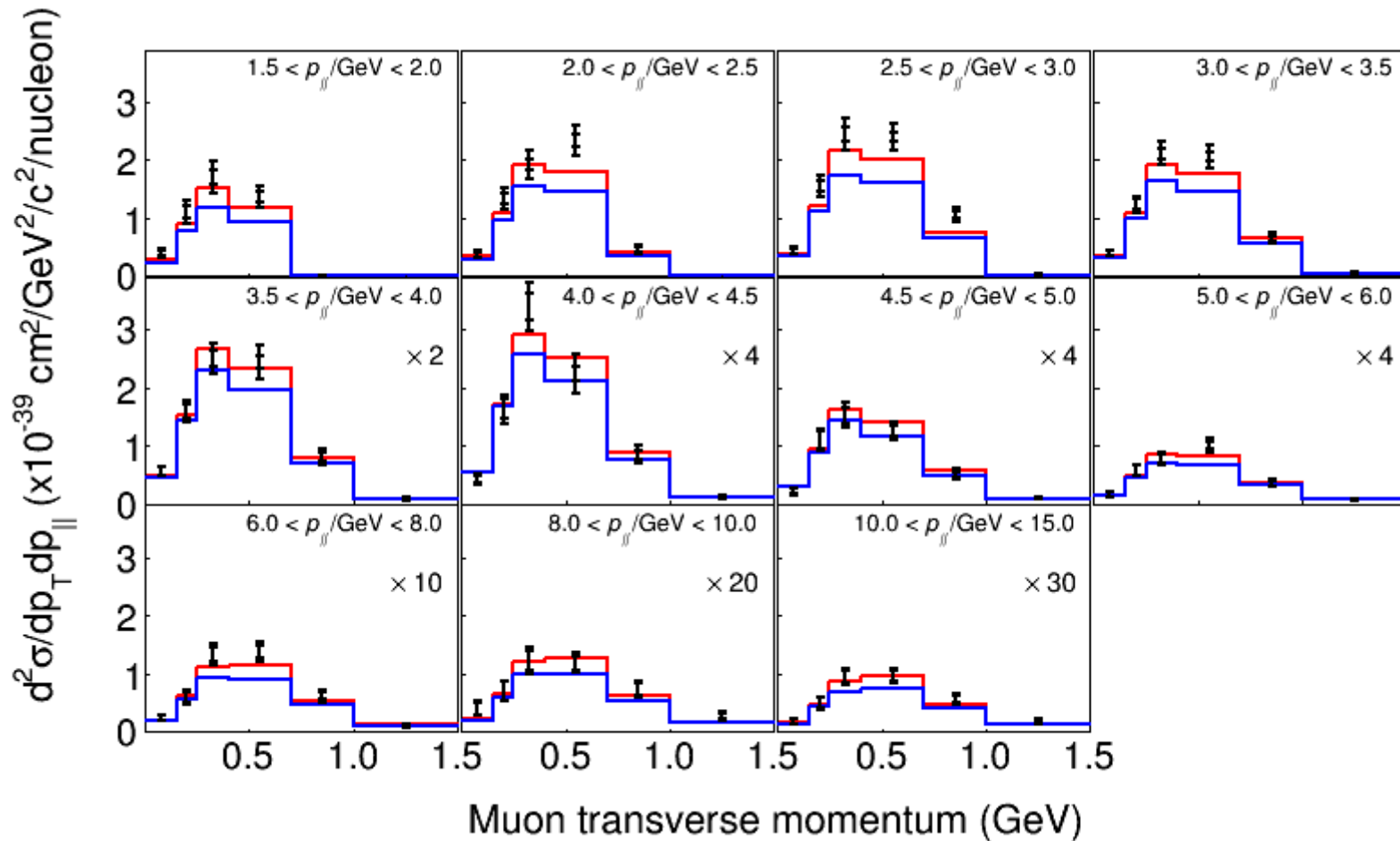
$p_{||}$ tracks E_{μ} and E_{ν} closely, p_{\perp} tracks momentum transfer

MINERvA tune based on inclusive sample is better.

Many of the same events, but different use of observables.

QE-like events (no pion) viewed from muon kinematics for Anti-neutrinos

C. Patrick, [MINERvA], in preparation



GENIE
2.8.4

MINERvA
Tune v1
is better

MINERvA tune based on neutrino inclusive sample is better.

the 2p2h tune parameters are from the neutrino sample

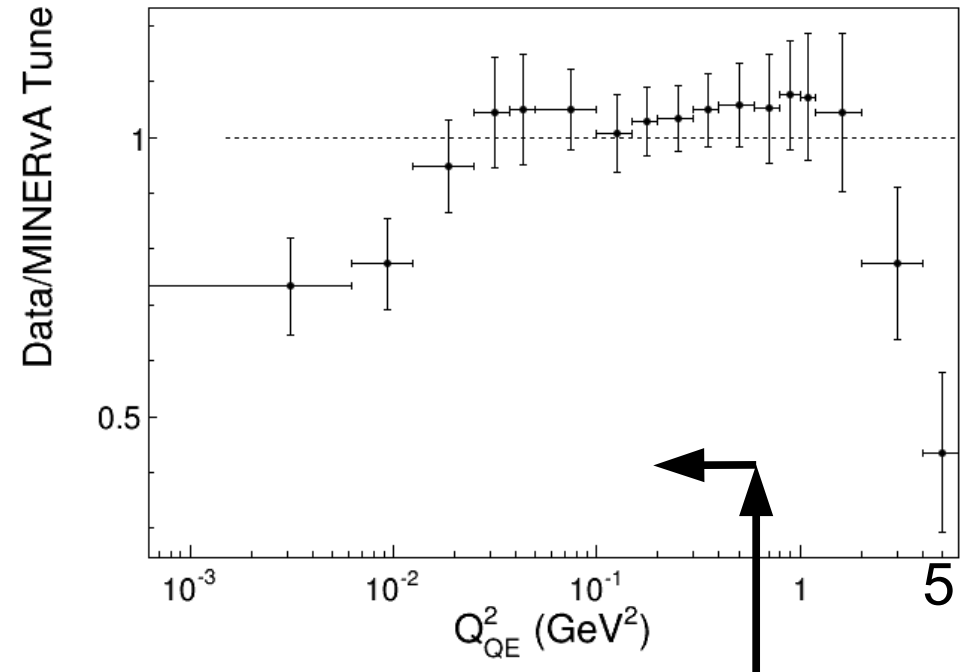
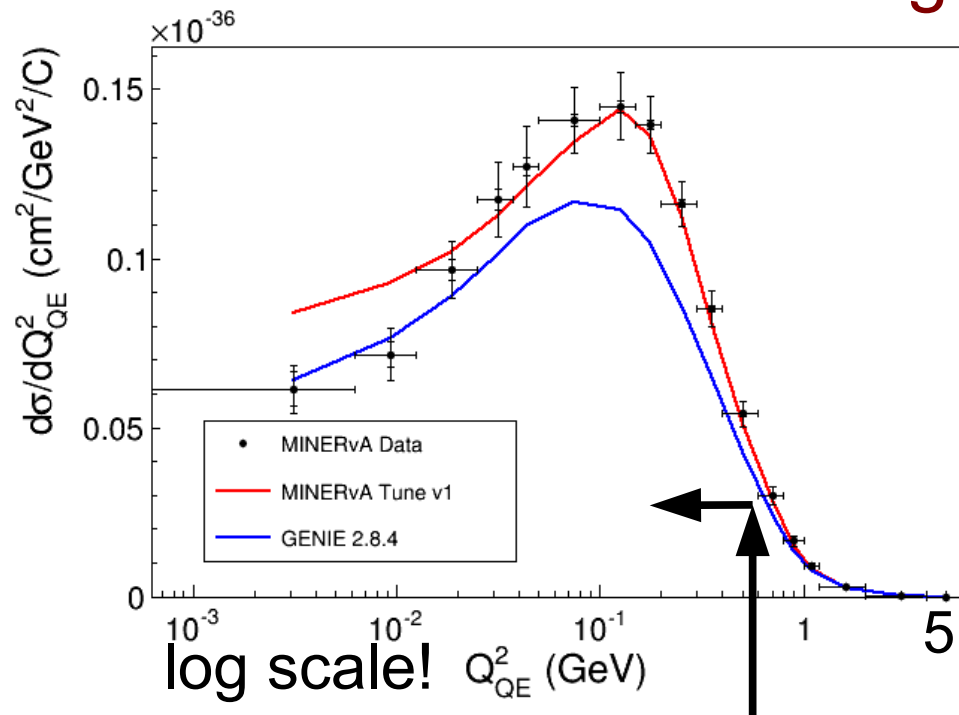
Many of the same events, but different use of observables.

QE-like events (no pion) in Q2 with QE hypothesis

For real QE events, collapsing this onto Q2 makes sense.

What caused trouble for our community for a long time
was non-QE events (2p2h and Delta with no pion)

they show up somewhere in this distribution, mixed with QE
so we were/are measuring the mix, not the Q2 distribution



extra kinematic reach !

this high- Q^2 reach goes up to 5 GeV², form factor sensitivity
small fraction of event rate, large fraction of range

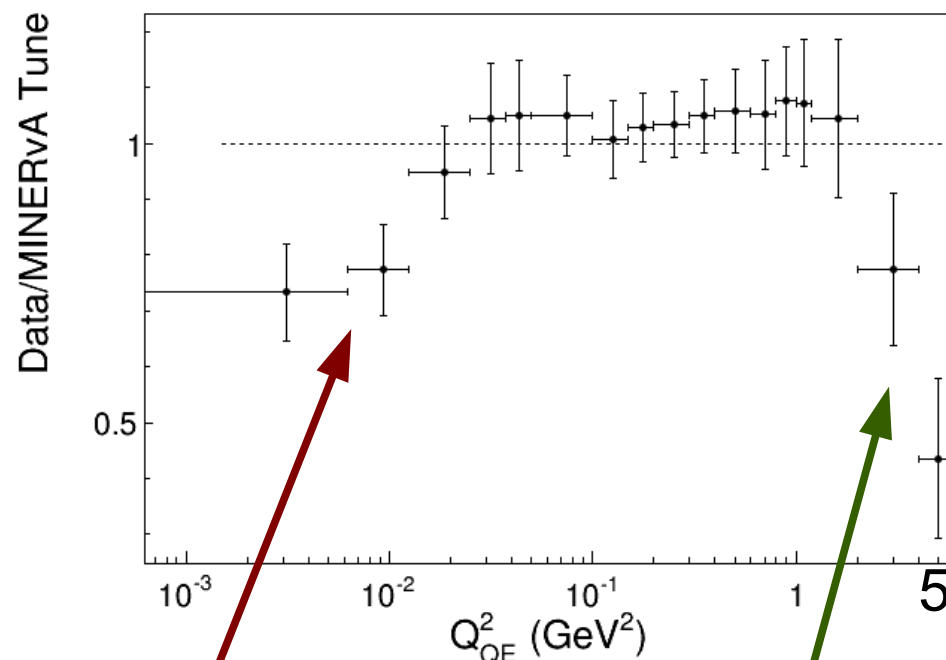
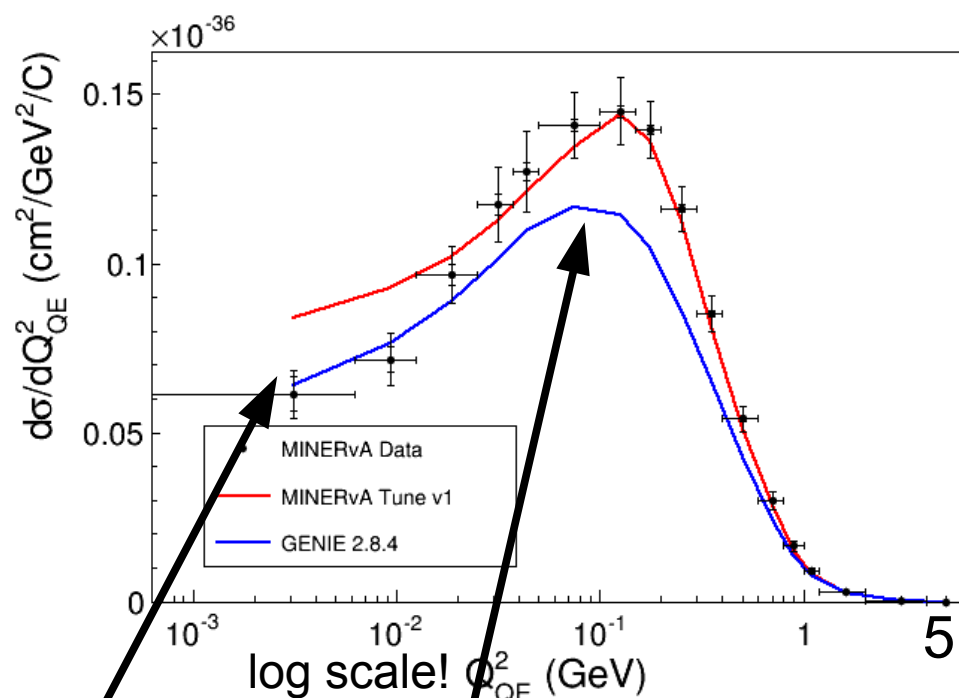
Proposed interpretation: QE-like events (no pion) in Q2

For real QE events, collapsing this onto Q2 makes sense.

The no-pion Δ component is large fraction at lowest Q2

The high Q2 component is especially sensitive to form factor

Things look good in the middle, like in the inclusive analysis.

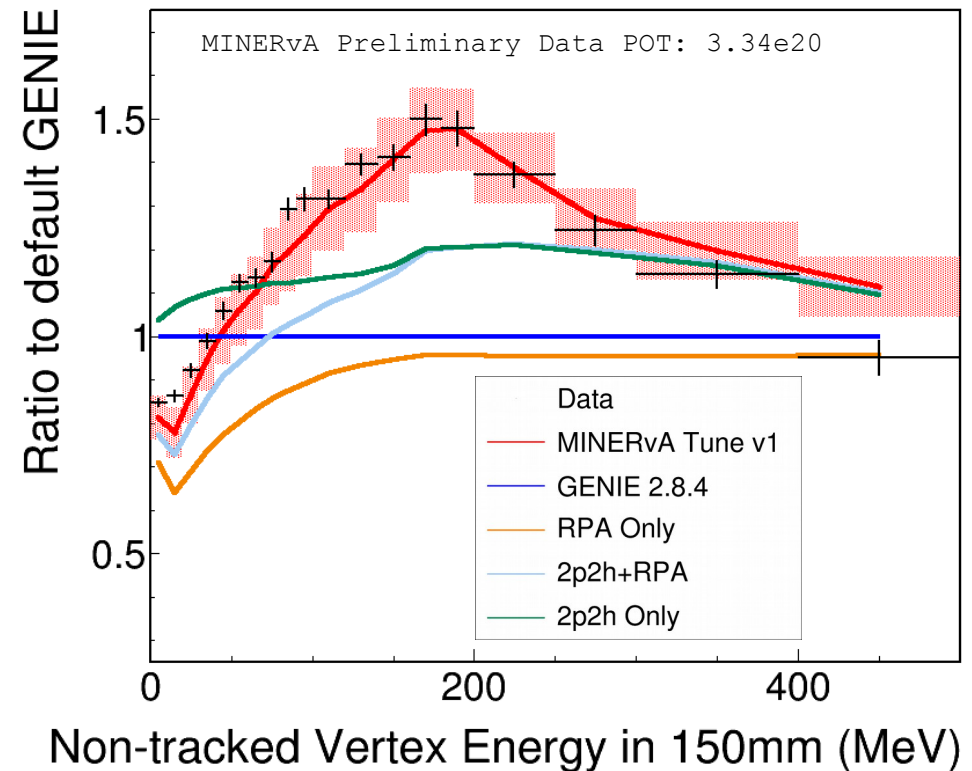
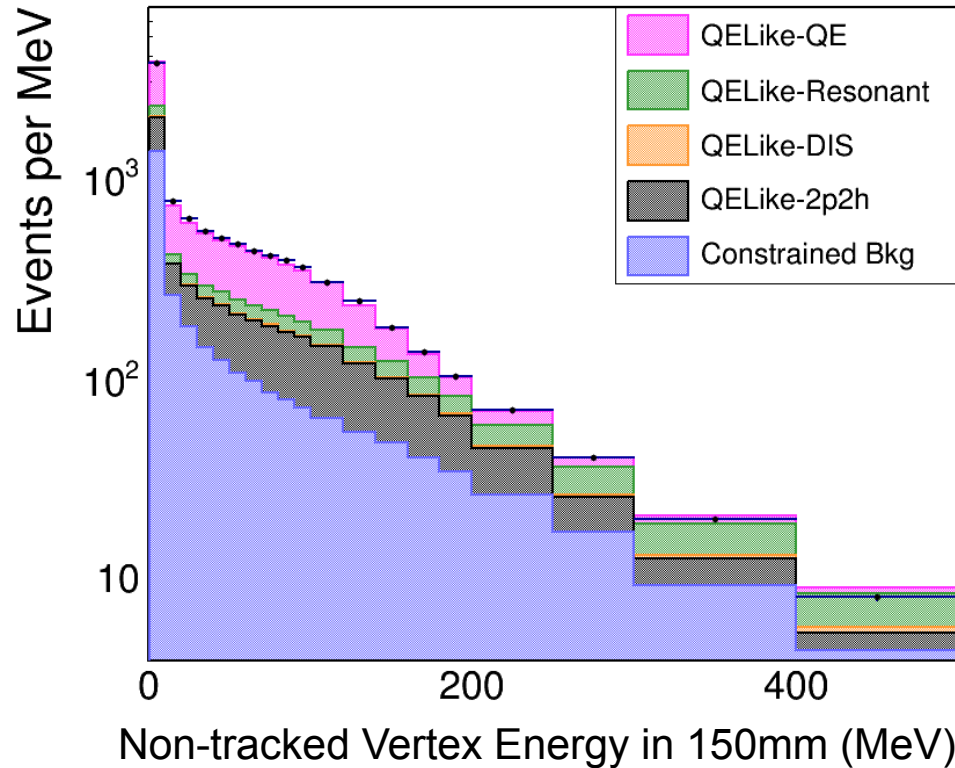


need RPA and 2p2h. low-Q2 Δ -no-pion still mis-modeled?

high-Q2 QE is mis-modeled. axial form factor?

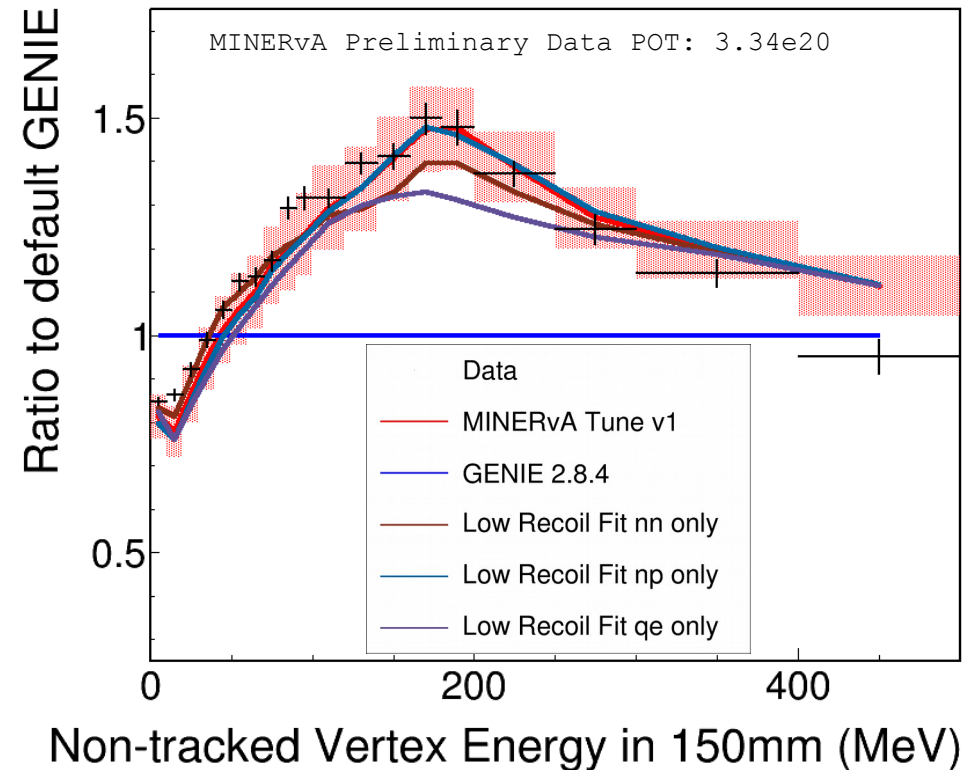
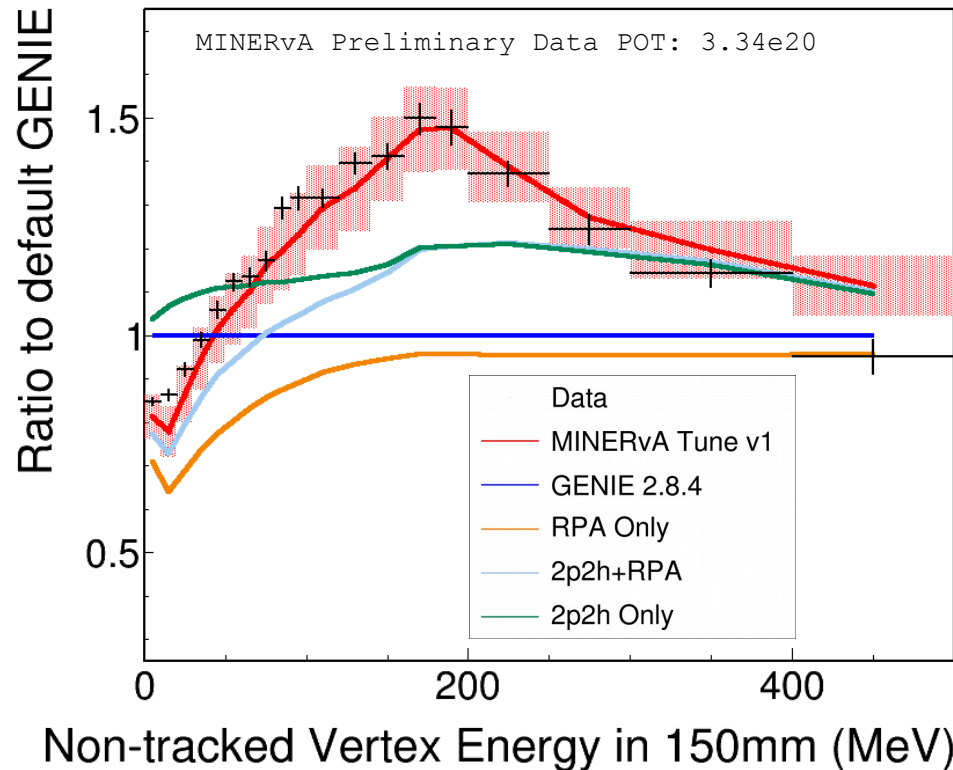
looks more like the z expansion Deuterium re-analysis

Untracked hadron energy, ratio to GENIE 2.8.4



important distinction: tracked proton energy is not here
In the inclusive analysis, tracked protons and pions included,
So we have subdivided the observable E_{had} into two parts!
Red line agreement reinforces 2p2h and RPA-QE are needed
if the “problem” with GENIE 2.8.4 was only QE, would
expect agreement to start to diverge by now

Untracked hadron energy, four GENIE tunes!



The 2p2h tune actually comes in four variations!

The one that weights up all 2p2h works well.

Weighting only np initial pairs (pp final states) good in middle

Weighting up nn pairs ok at low end.

Weighting up QE (single p final state) not so good.

Room for model builders and future analysis at 10% level

can be used as an error band for many purposes

Third example: QE-like (no pions) proton kinematics

The previous hadron energy distribution
was untracked energy
and ignored tracked protons.

So clever things about those protons
for a two-body reaction.

we can totally invert the analysis
get a close look at final state rescattering model



(c)

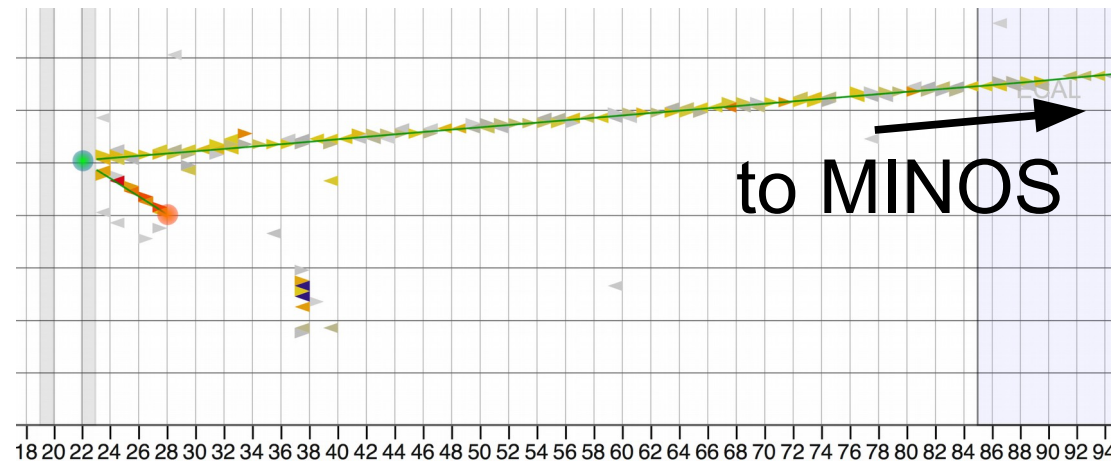
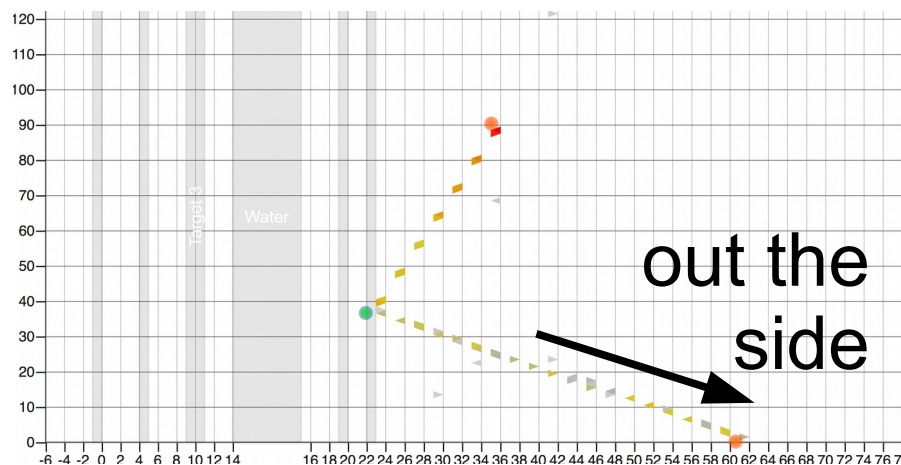
adorable
unfolded
kitten from
Glen Cowan's
Statistical Data
Analysis book

QE-like (no-pion) events viewed with proton kinematics

Betancourt, Ghosh, Walton, [MINERvA], PRL in press, arXiv:1705.03791

Require a muon but ignore (!!) its particulars
insist on one tracked proton and no pions

This sample goes beyond the previous in two ways:
1. add high angle muon events that leave out the side



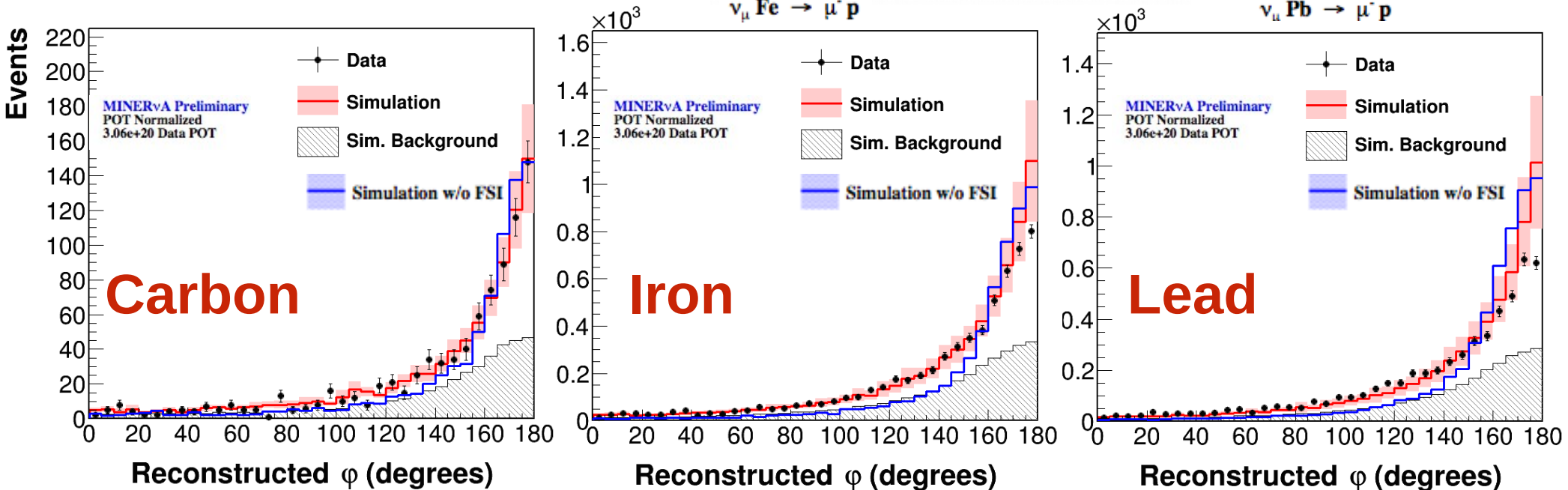
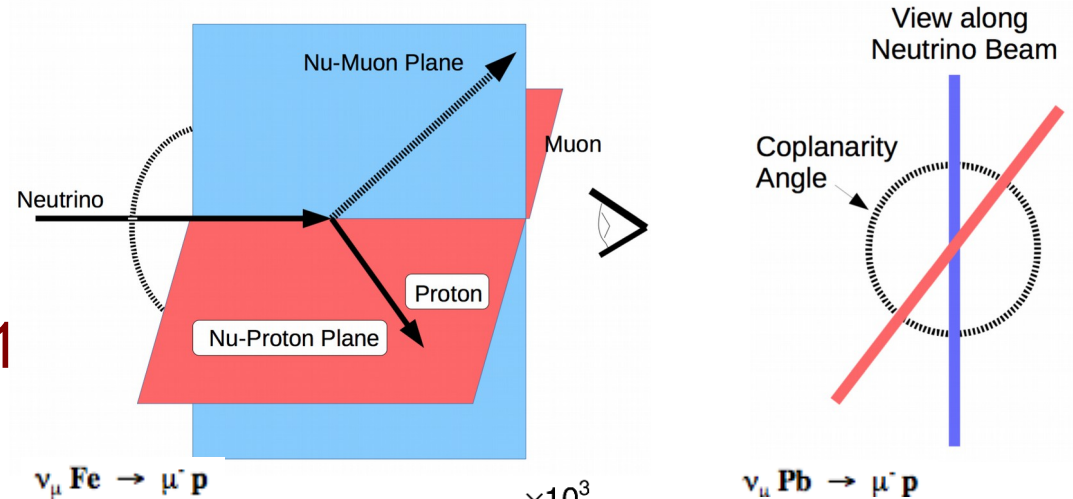
2. run this in the nuclear target region with Pb, Fe, C
and measure A-dependence of intranuclear rescattering
because it will show up most strongly in the
proton energy and direction distributions

Coplanarity Angle

very different quantity
than semi-inclusive ones

Simulation is MINERvA tune v1

Blue: turn off FSI rescattering



Discrepancy at 180 (most QE-like) grows with nucleus size

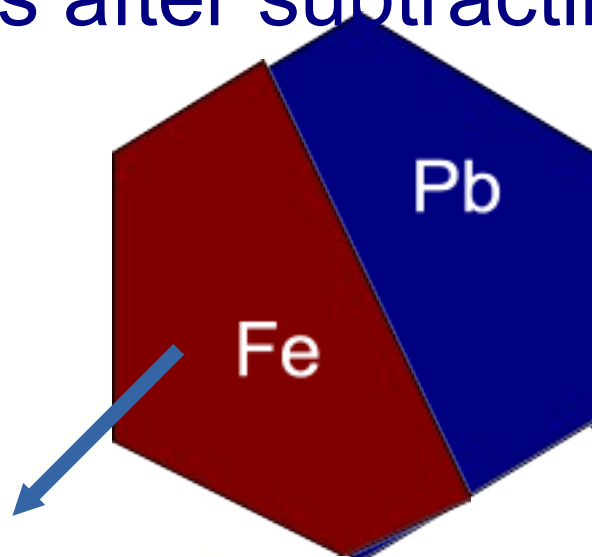
Simulation without FSI rescattering is even worse.

Preliminary interpretation, GENIE is missing some

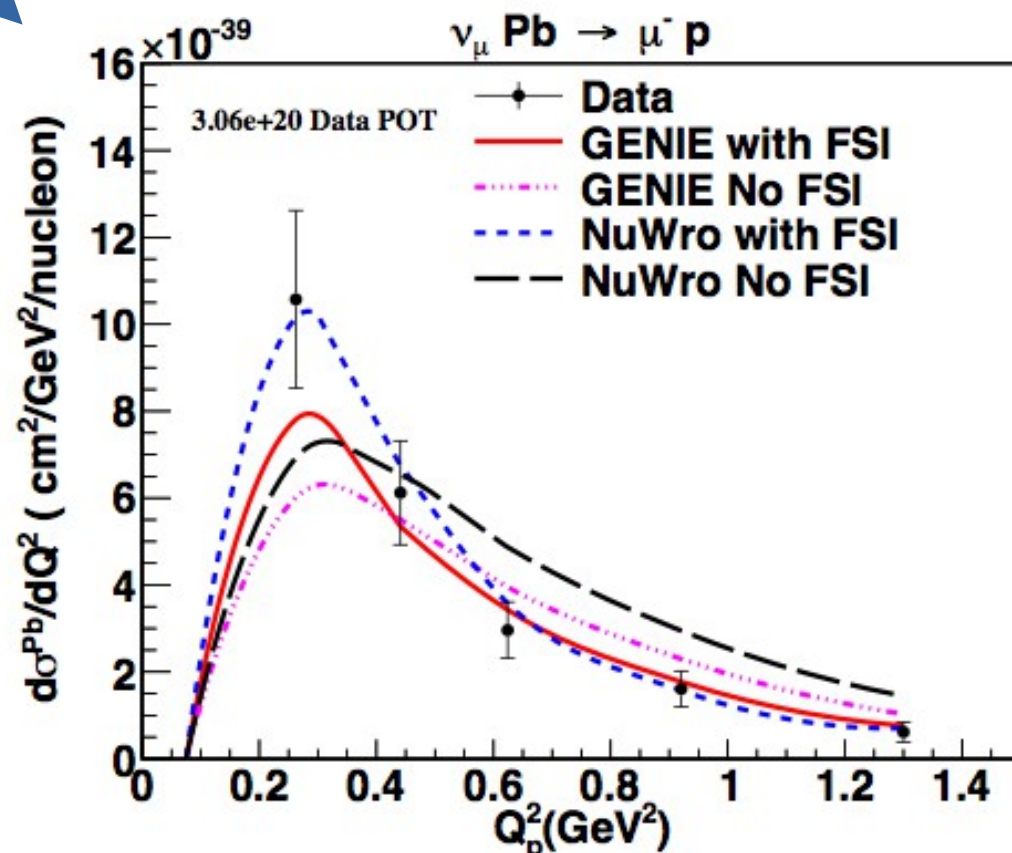
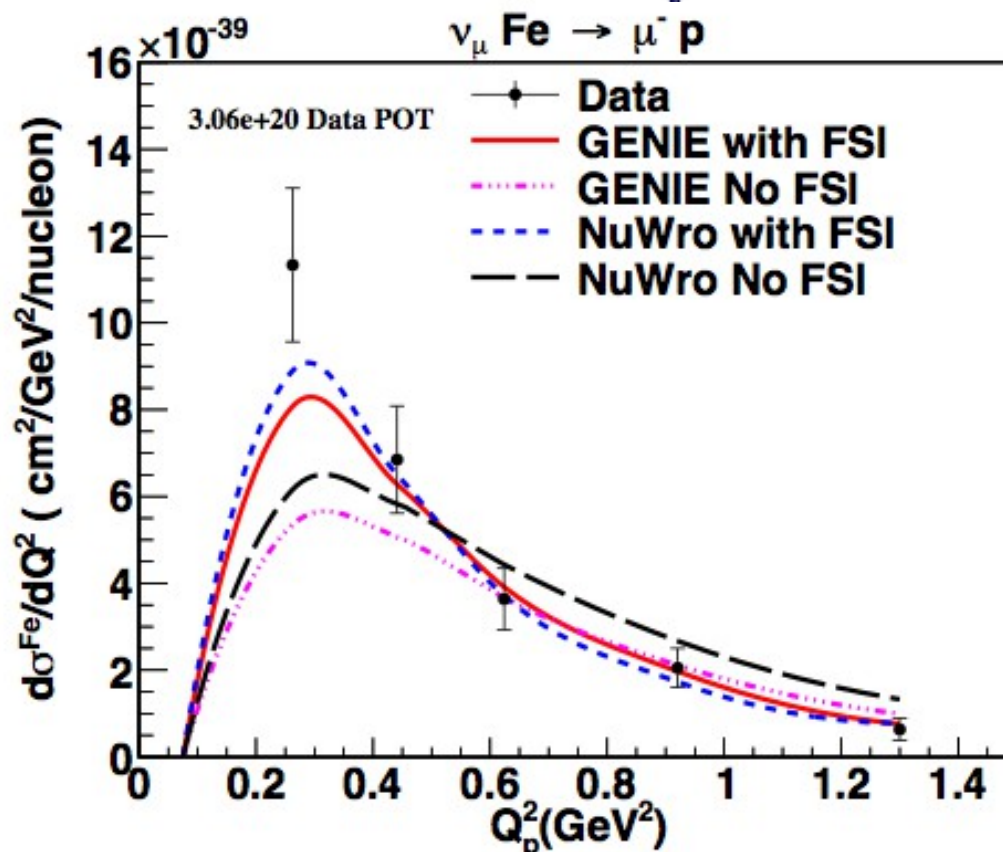
A-dependent aspect of the FSI rescattering.

Revised version of GENIE pion absorption forthcoming.

Results after subtracting background and unfolding



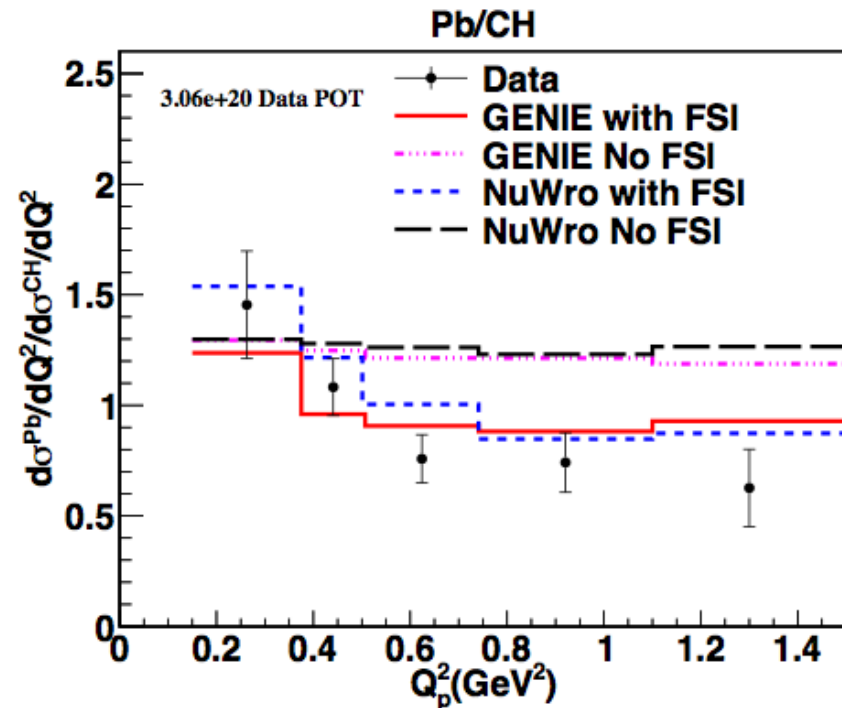
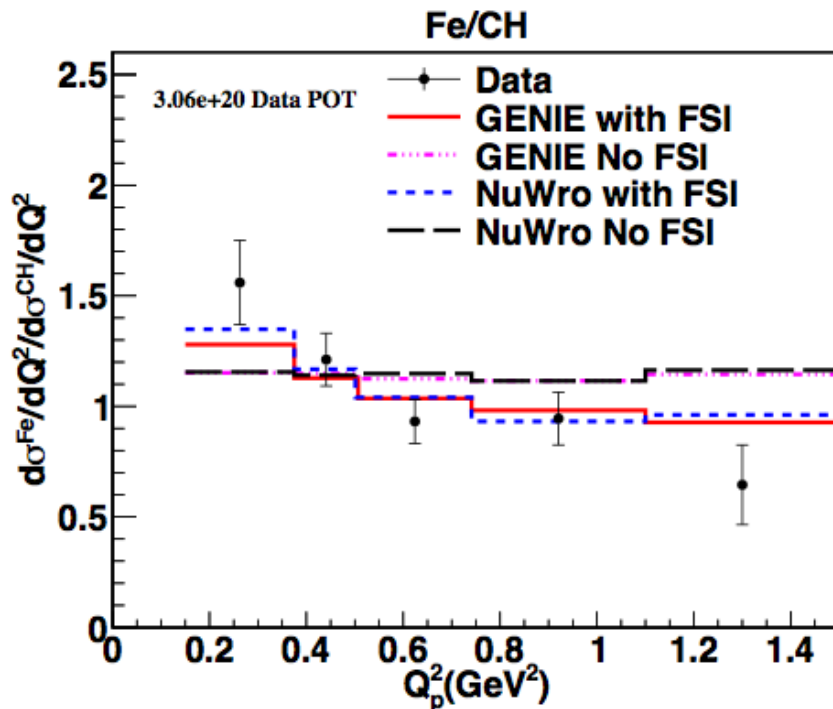
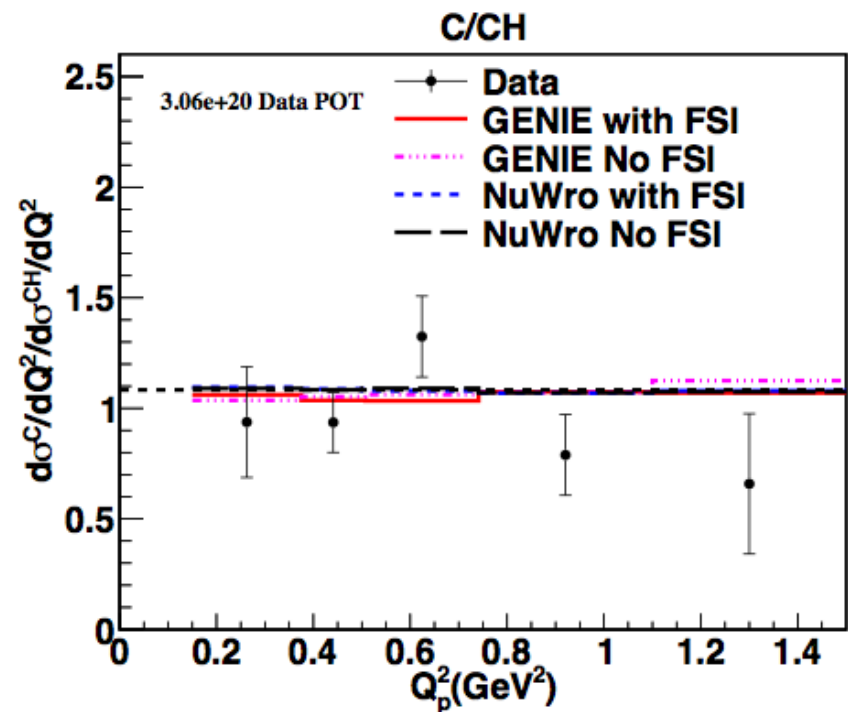
GENIE has weak A dependence but NuWro FSI (Oset model) has a strong dependence that better describes data



This Q^2 axis is equivalent (linear transformation) of the proton KE

Cross section ratios

Smaller systematic uncertainty
Fe/CH and Pb/CH need FSI
GENIE, NuWro about right
and the more A-dependent FSI
NuWro is preferred in first bin
(where the distribution peaks)





Final example
How about events
with pions
outside the nucleus?

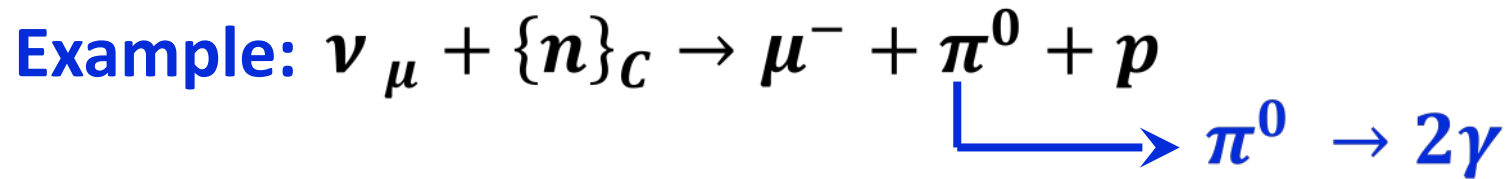
Saint Surrounded by Three Pi Mesons

Salvador Dalí
Figueres, Spain, 1957

obviously is a portrait
of exchange pions
in the nucleus...

we want real pions 39

Start with our newest, the neutral pion channel

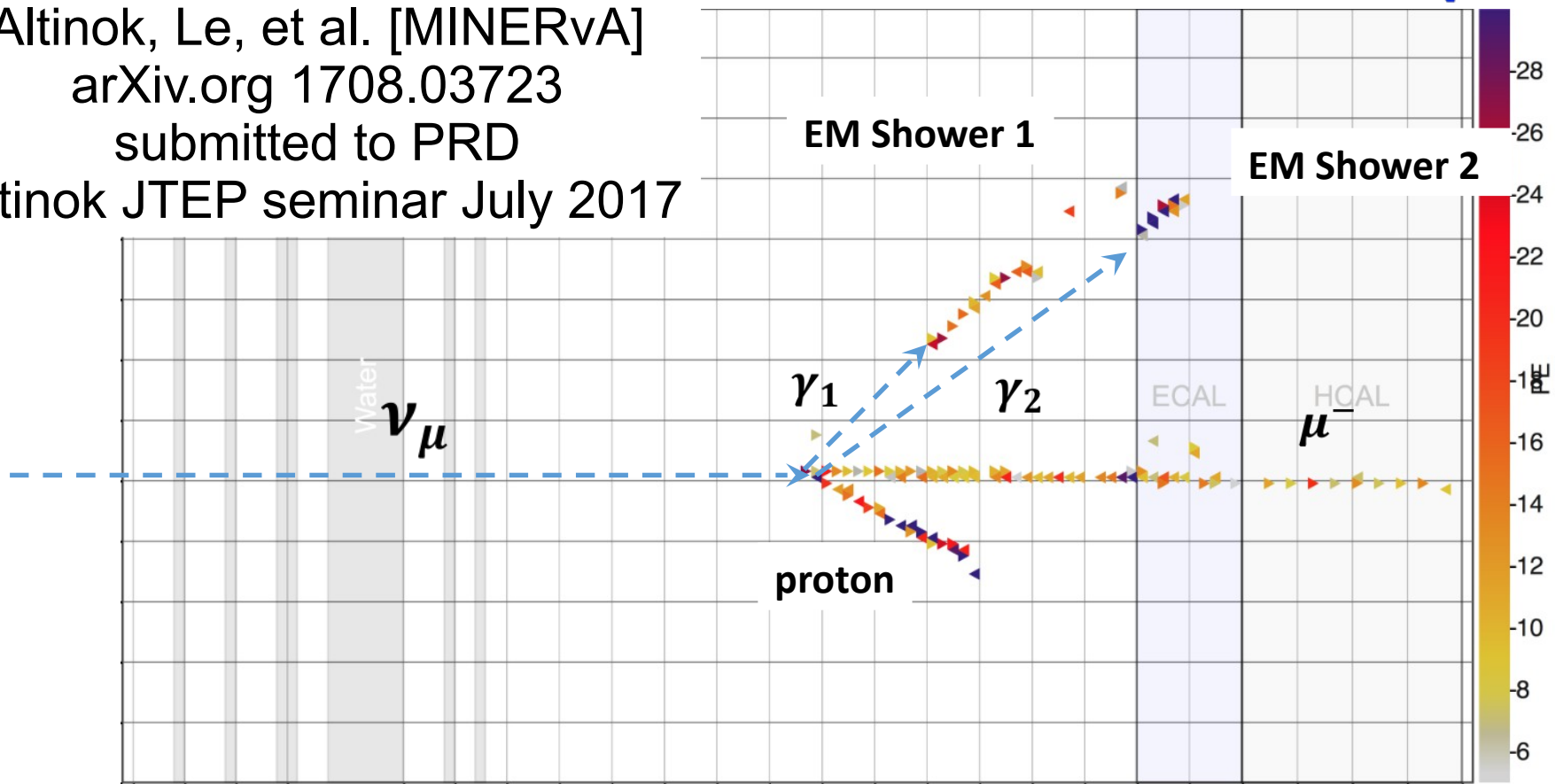


Altinok, Le, et al. [MINERvA]

arXiv.org 1708.03723

submitted to PRD

Altinok JTEP seminar July 2017



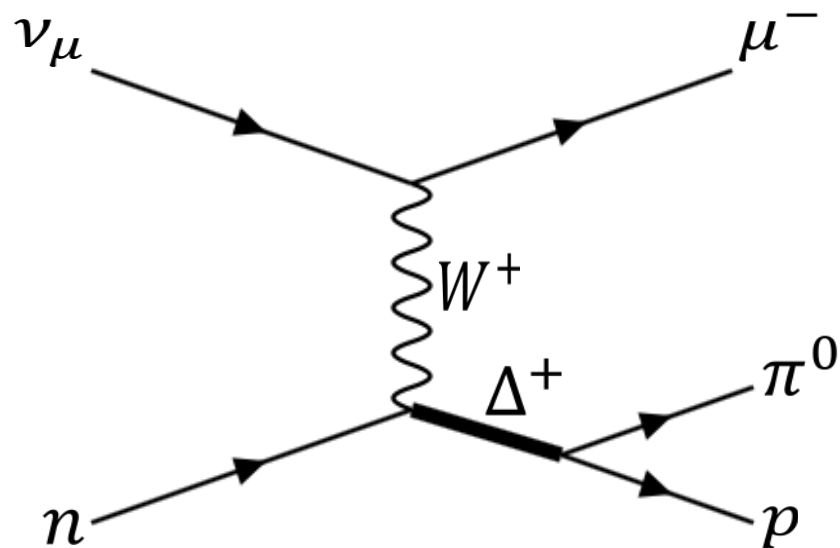
We track and identify charged pions too especially π^+ with their Michel decay signature but with a higher pion energy detection threshold

Two interesting diagrams contribute to pion production

All generators include these components, but use different mixtures and prescriptions

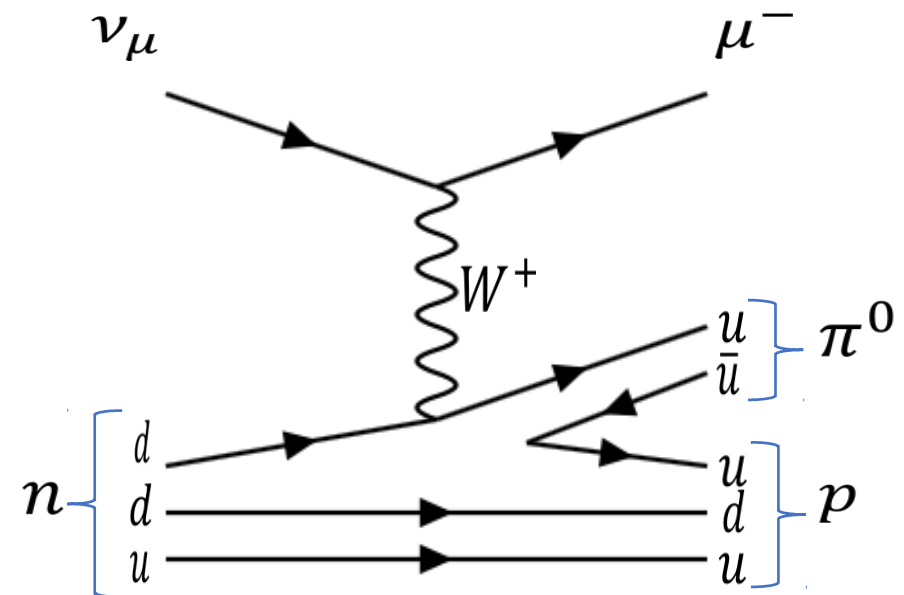
Baryon Resonance Production

$\Delta^+(1232)$, higher-mass N^*



$W = 1.2 \text{ GeV}$
(also 1.5, 1.7)

Non-Resonant Production and Deep Inelastic Scattering

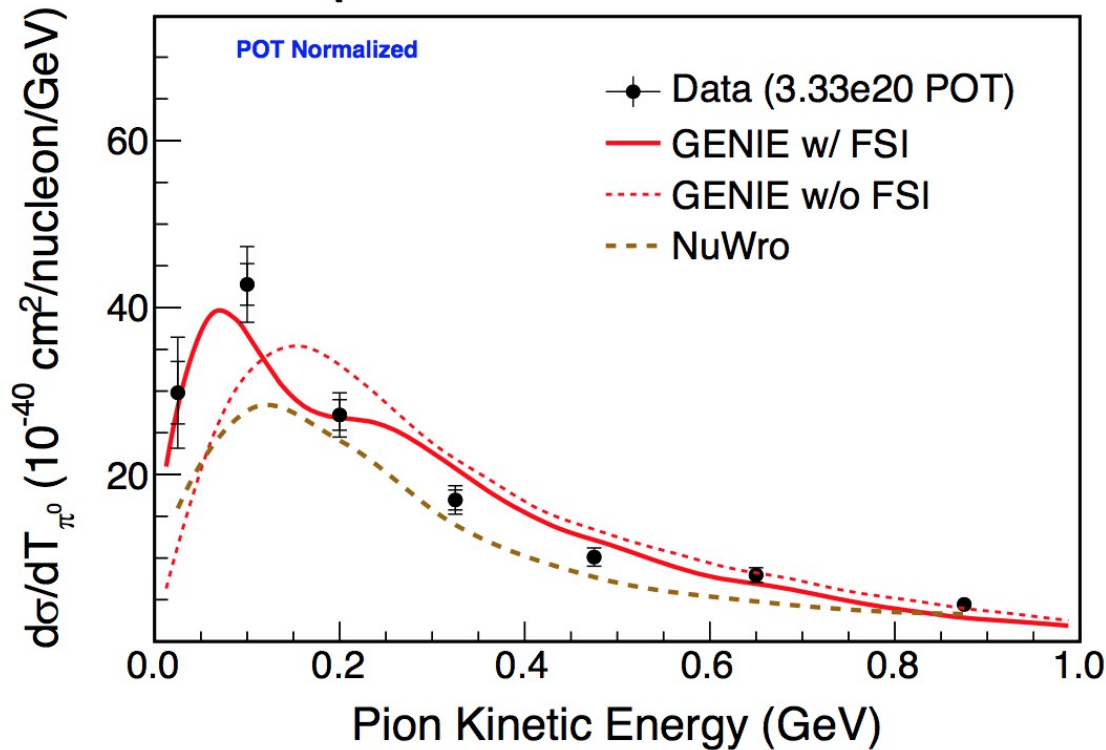
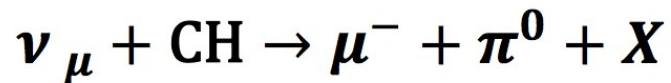


some at all W
continuum

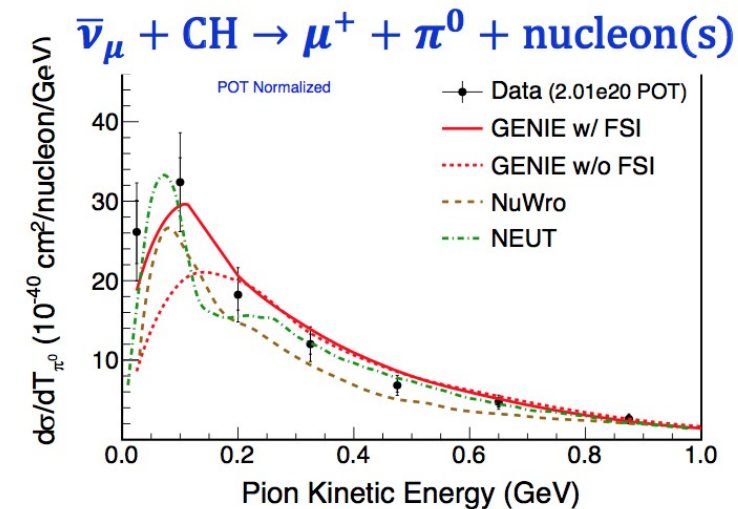
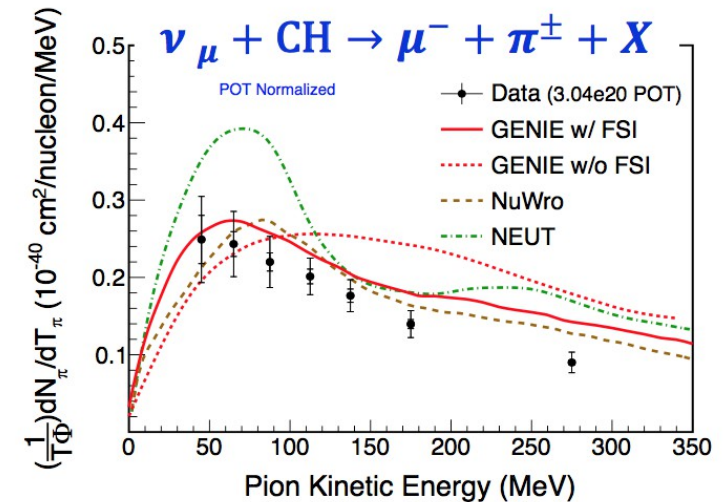
Resulting hadrons rescatter as they exit the nucleus

Pion kinetic energy

Latest result, Altinok W&C July



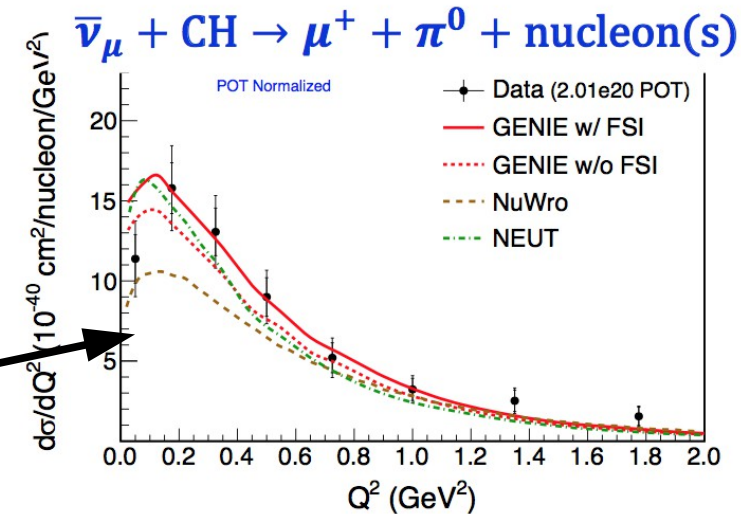
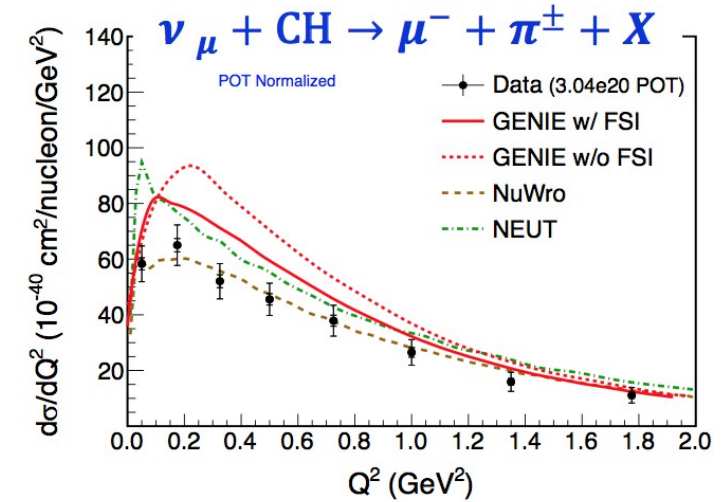
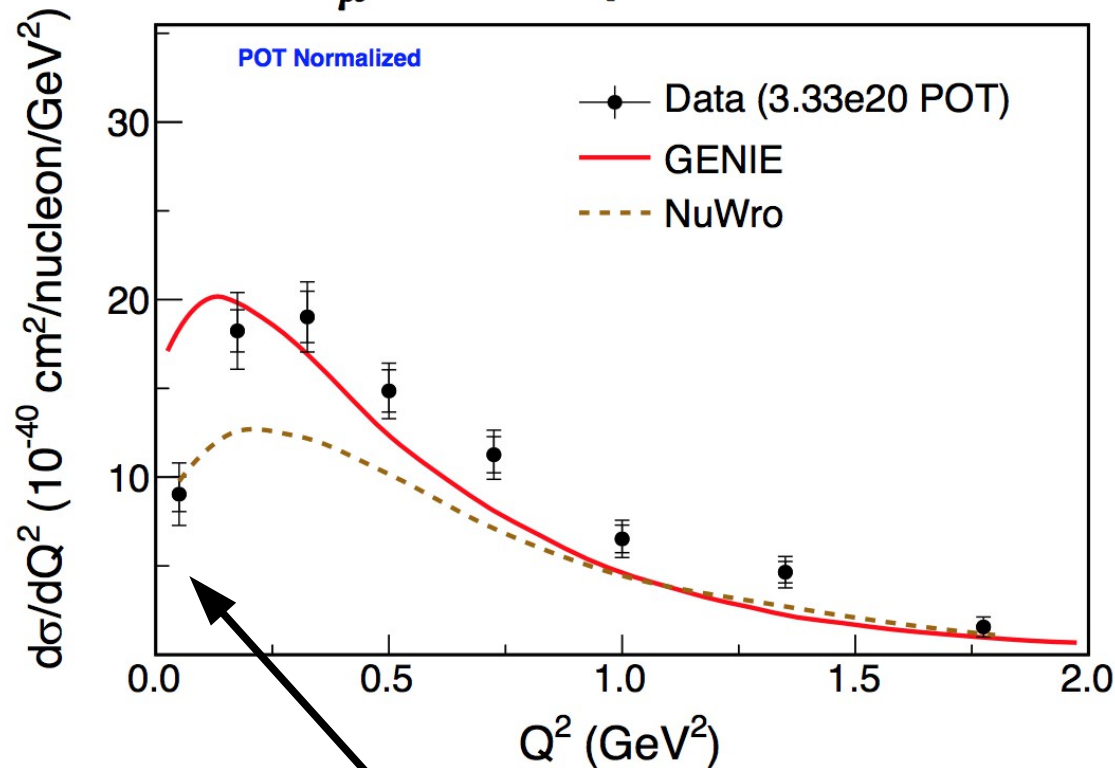
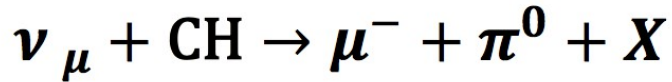
Previously reported measurement channels



FSI is essential feed-down to low energy
and feed in/out of the sub-dominant / dominant isospin
GENIE pretty good. NuWro is always lower than GENIE

Reconstructed Q2 from calorimetry

$$Q^2 = 2E_\nu(E_\nu - p_\mu \cos \theta_{\mu\nu}) - m_\mu^2$$



Major overprediction at lowest Q2

with pion matches observations without pion and inclusive
appears like an RPA-effect but for Delta and transition ₄₃

Conclusions

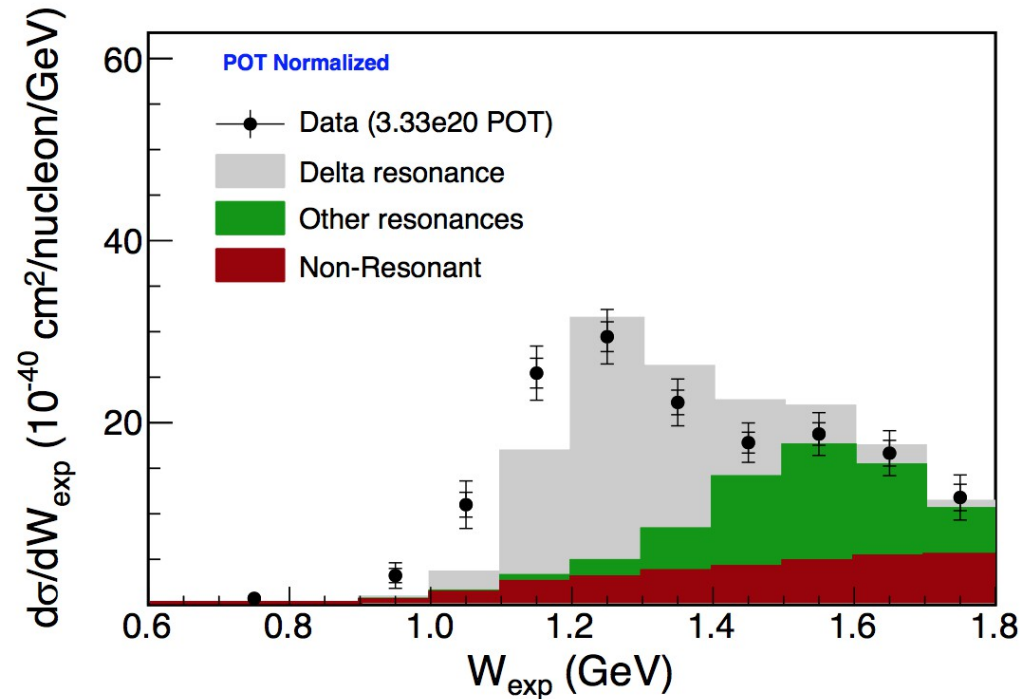
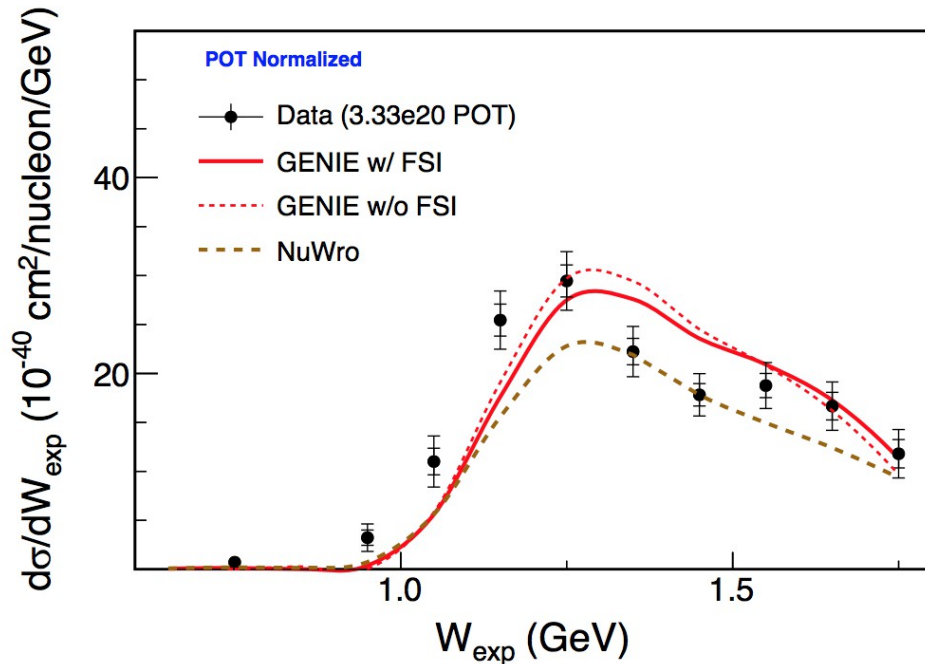
Multiple ways of looking at data from QE to resonance using many observables in different combinations are described ok with GENIE FSI, RPA-modified QE and a 2p2h process (and some low-Q² resonance suppression)

The tune we present serves as a baseline for current and future analyses and model building we are now exploring effects at the $\pm 10\%$ level

Can be used as a set of uncertainty estimates to replace the old axial mass effective uncertainty with targeted 2p2h, RPA, and form factor uncertainties for cross section unfolding and oscillation studies

Reconstructed W from calorimetry

- W_{exp} is calculated using reco variables: $W_{\text{exp}} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$



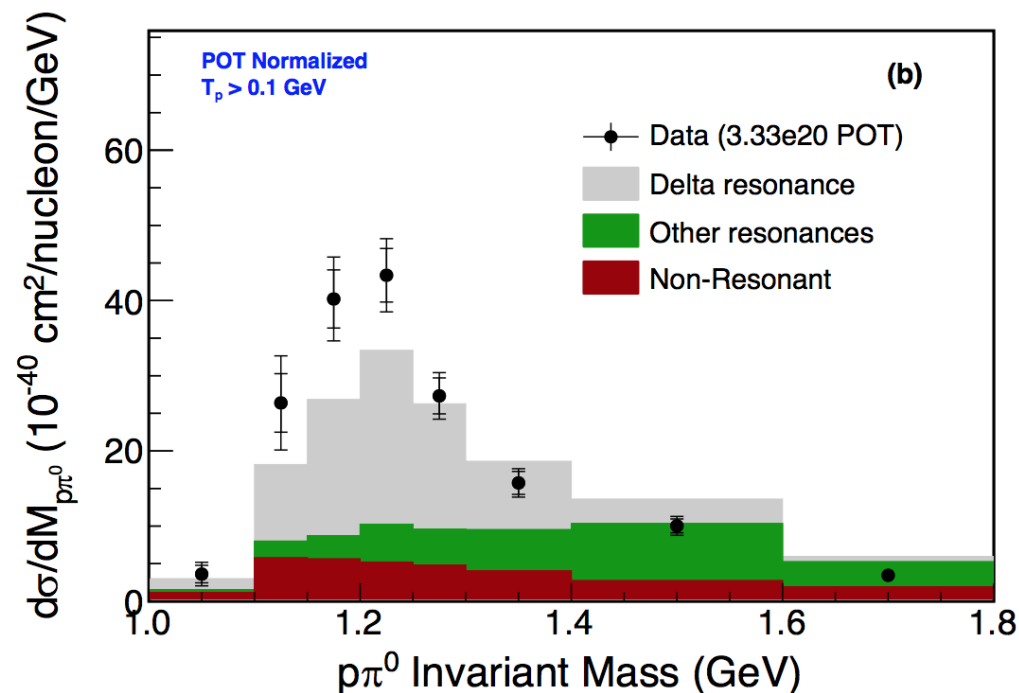
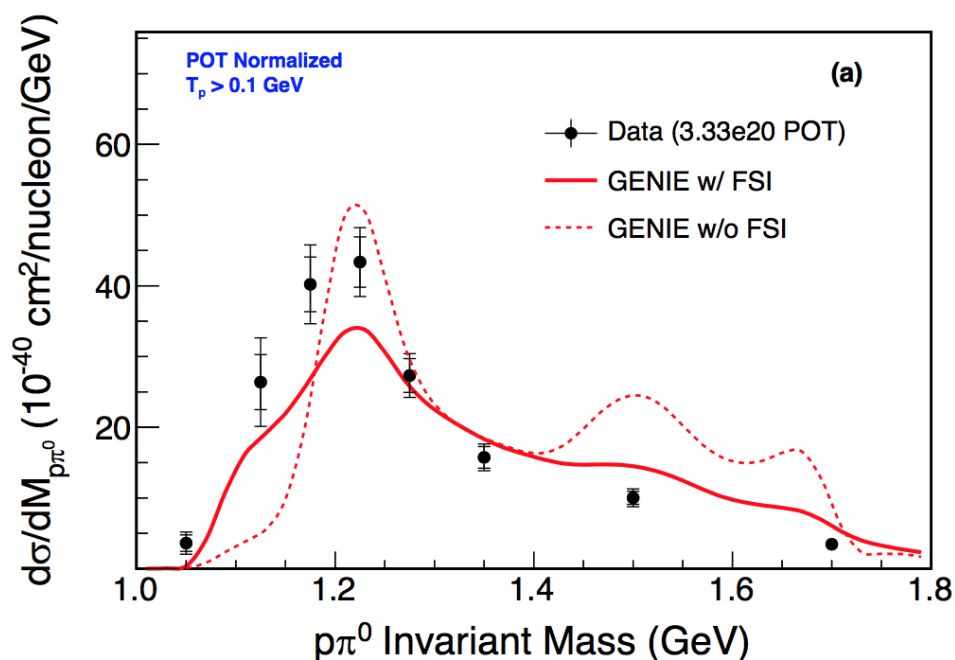
Simulation is appearing a little too far right (too high W)
like a shift of ~ 20 MeV, keeping the shape the same.

in-medium Δ width? Fermi motion, removal energy?

Interference between resonance and non-resonance process?

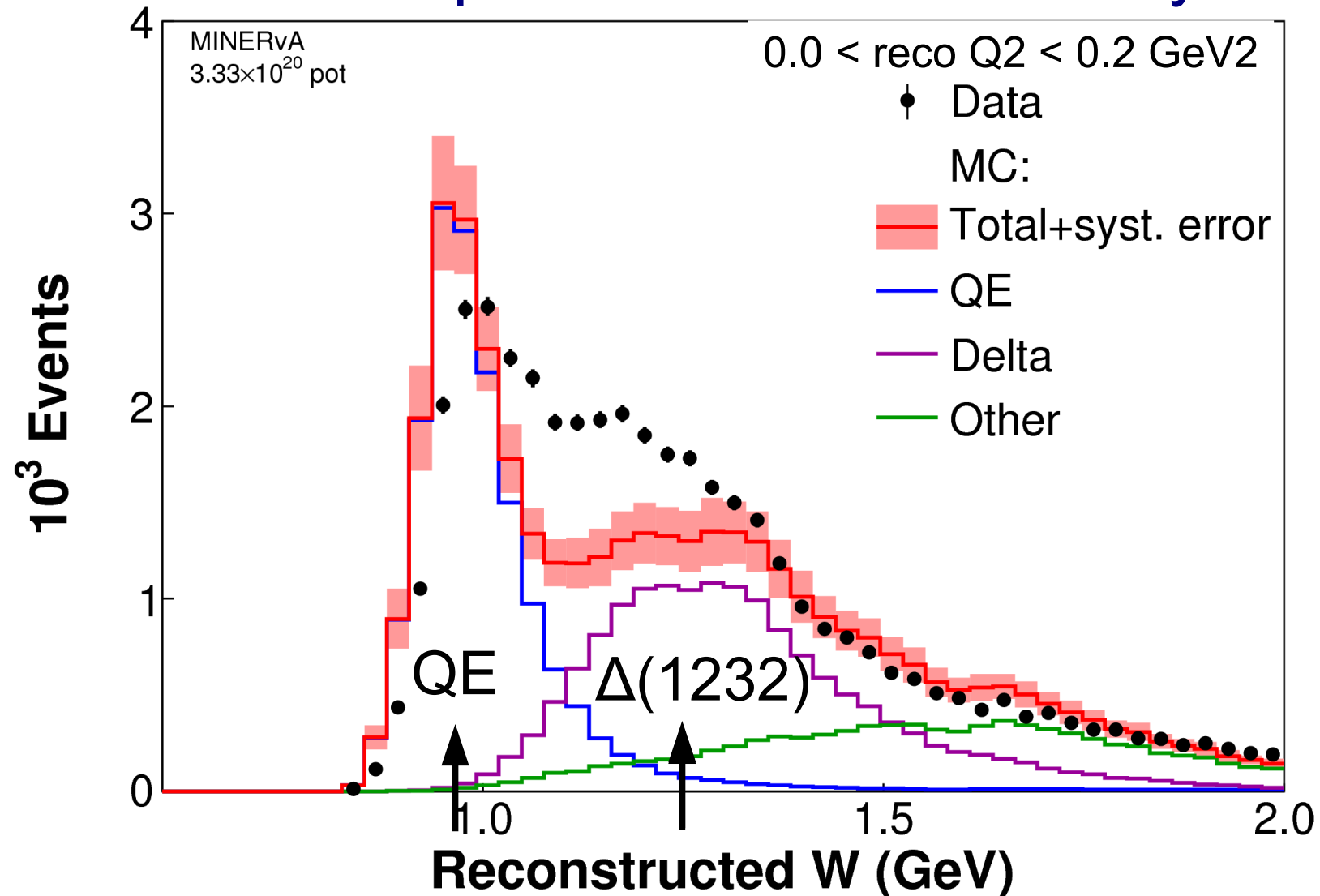
Reconstructed W from pion+proton system

- $p\pi^0$ Invariant Mass is calculated using proton and pion 4-momentums
- Proton kinetic energy, T_p , is required to be greater than 0.1 GeV
- Size of background subtracted sample = 1522 data events (48.8% of original sample)



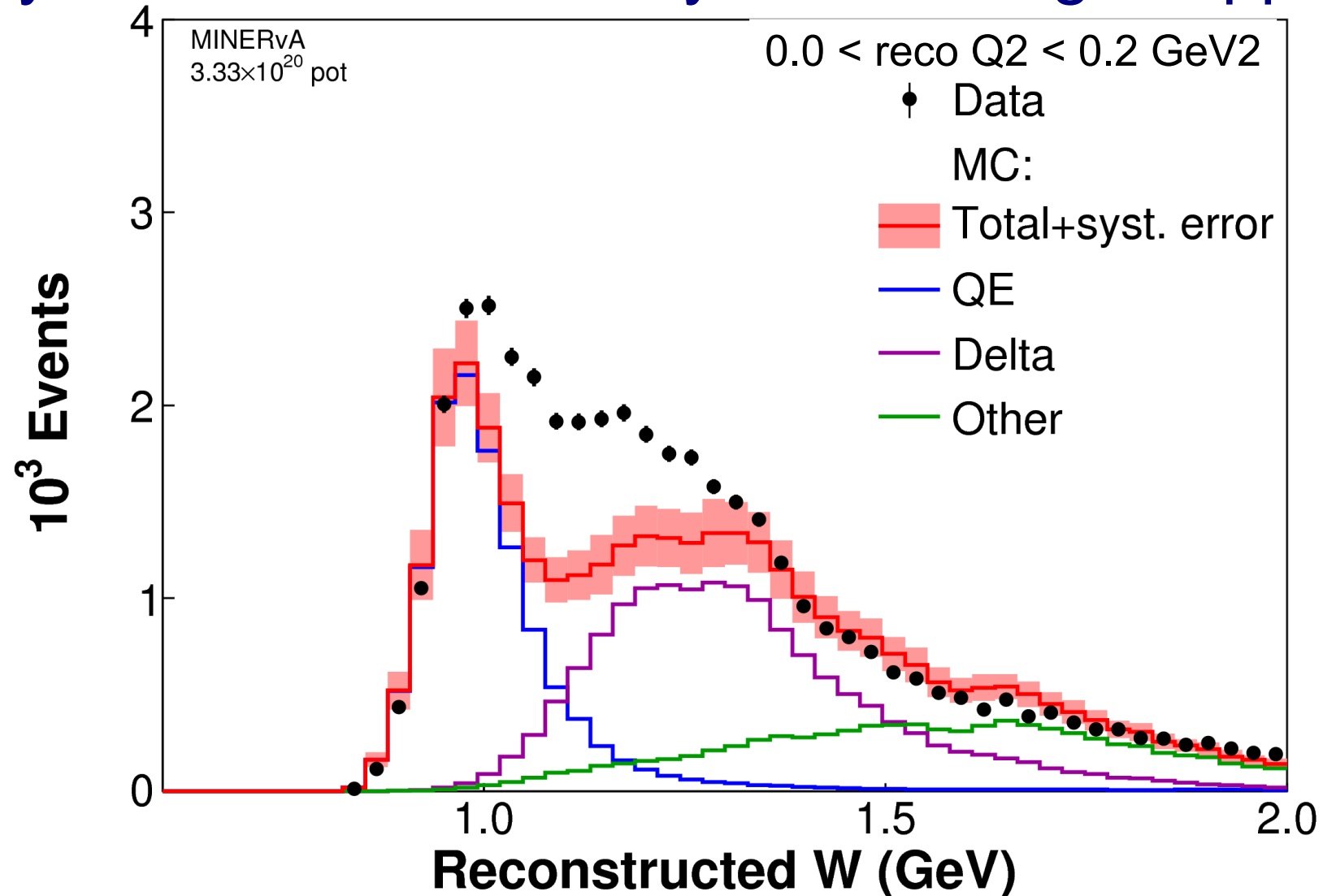
Similar story to previous slide with shift.
Also FSI is expected to wash out resonance structure
and the data wants that feature.

MINERvA data compared to model with only QE and Δ



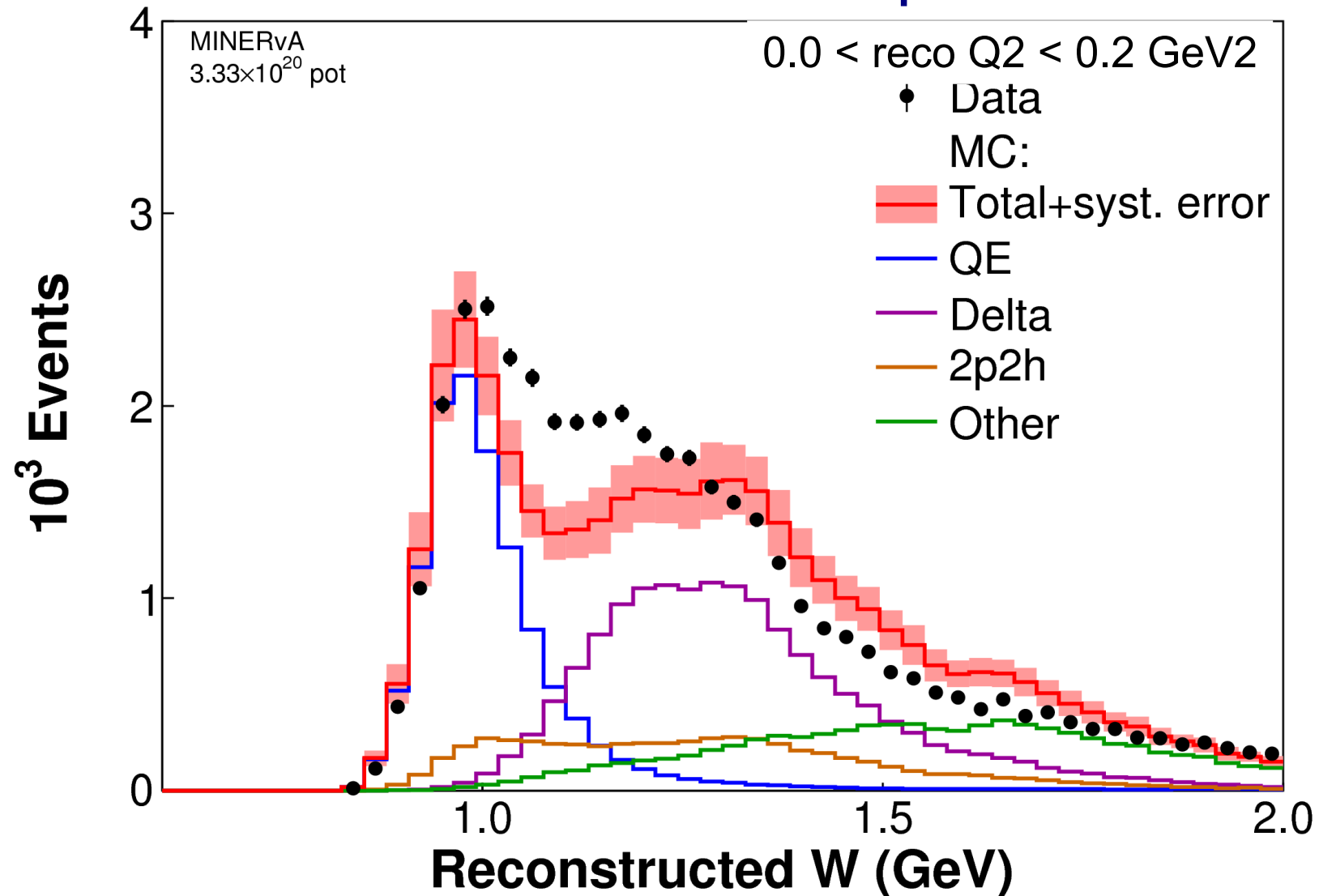
Fully simulated GENIE + MINERvA tuned pion
(GENIE is the name of a neutrino interaction computer code)
something is funny about the QE
and the data might have a 2p2h process in the dip

Modify model with “RPA”-style screening / suppression



RPA is a technique to model a screening of the nucleon significant as momentum-transfers approach zero. Nucleon equivalent to the polarization screening effect. Valencia RPA model for QE is tuned to muon capture data

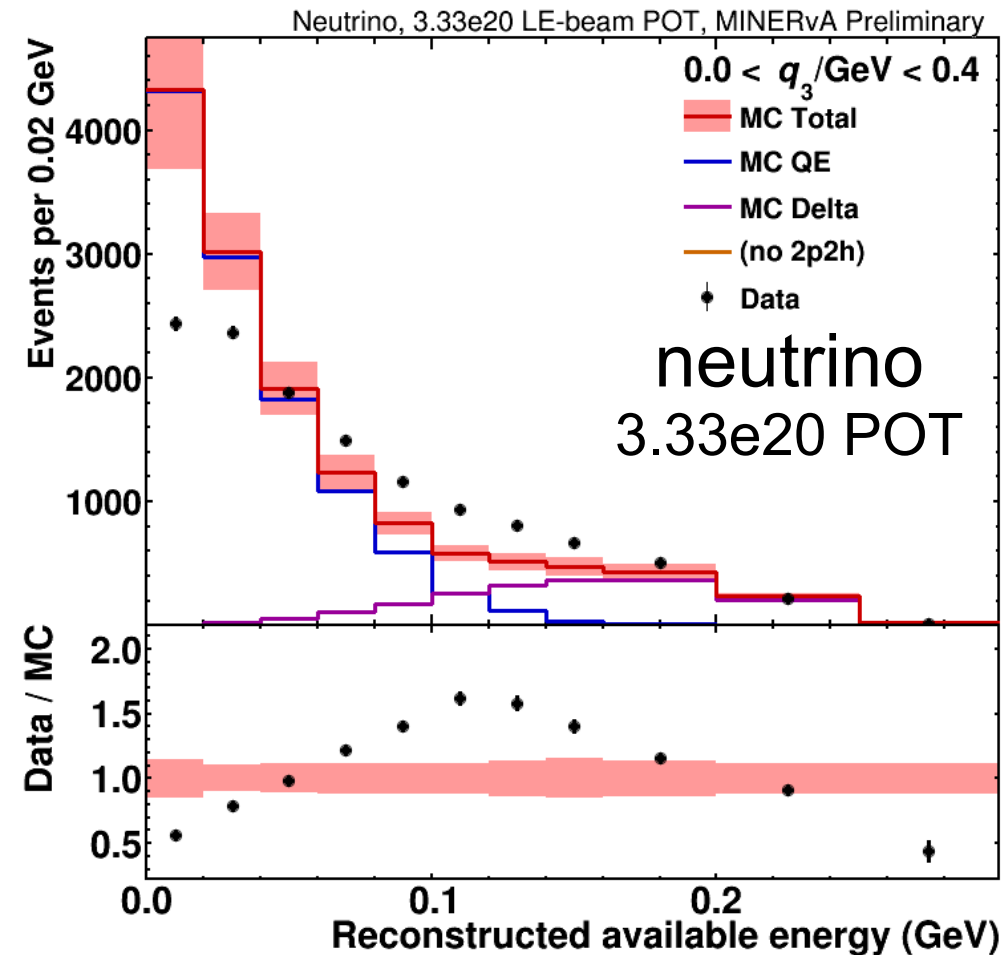
QE with RPA and Valencia 2p2h interactions



The 2p2h process contributes broadly
fills in the region between QE and Δ
does not produce perfect agreement – need more?

$q_3 < 0.4$ GeV, GENIE, pion base, no RPA, no 2p2h

X2 = 407 for 21 bins



Flipbook order
GENIE, no RPA, no 2p2h
yes RPA, no 2p2h
yes RPA, yes 2p2h
yes RPA, yes “tuned” 2p2h

fun fact! stat errors will often
be too small to see!

Chisquare with systematics is
three q_3 panels on prev. slide

What to look for:

Does the ratio look more flat? Closer to 1.0 + error band?

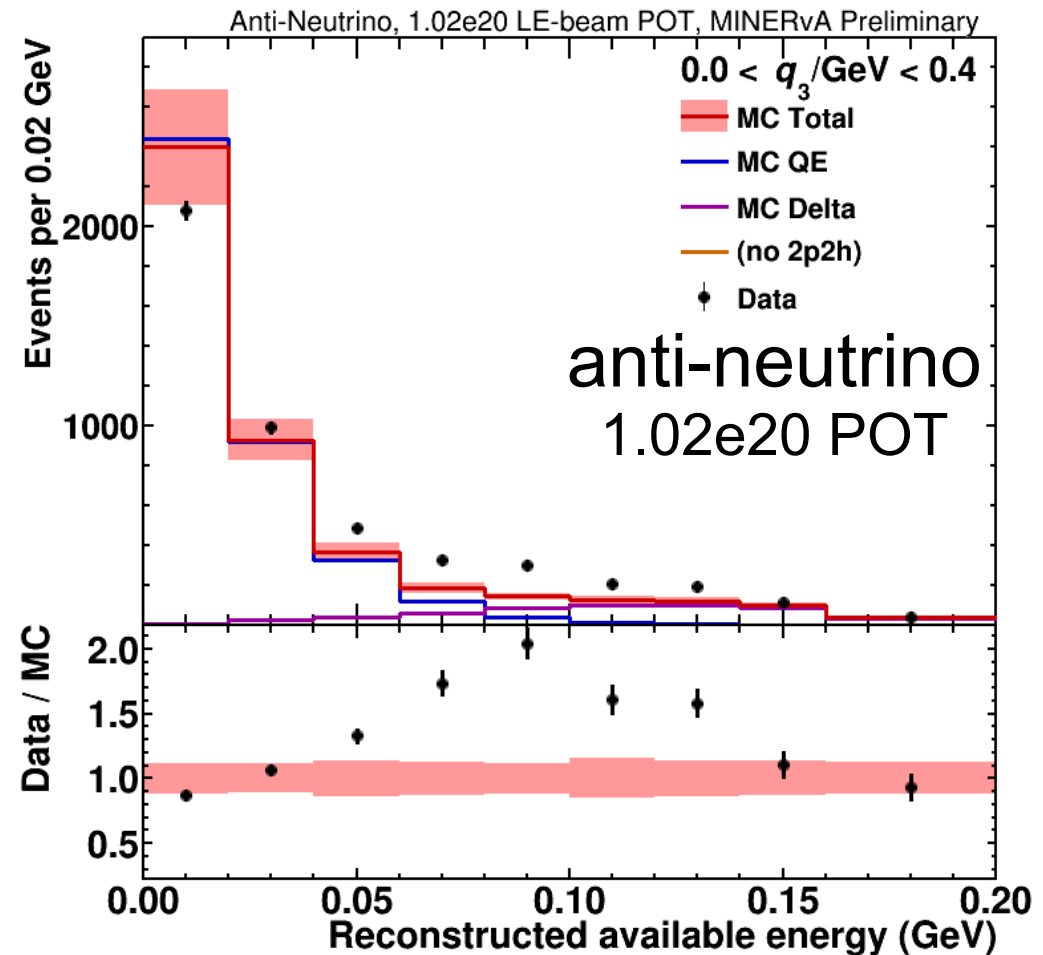
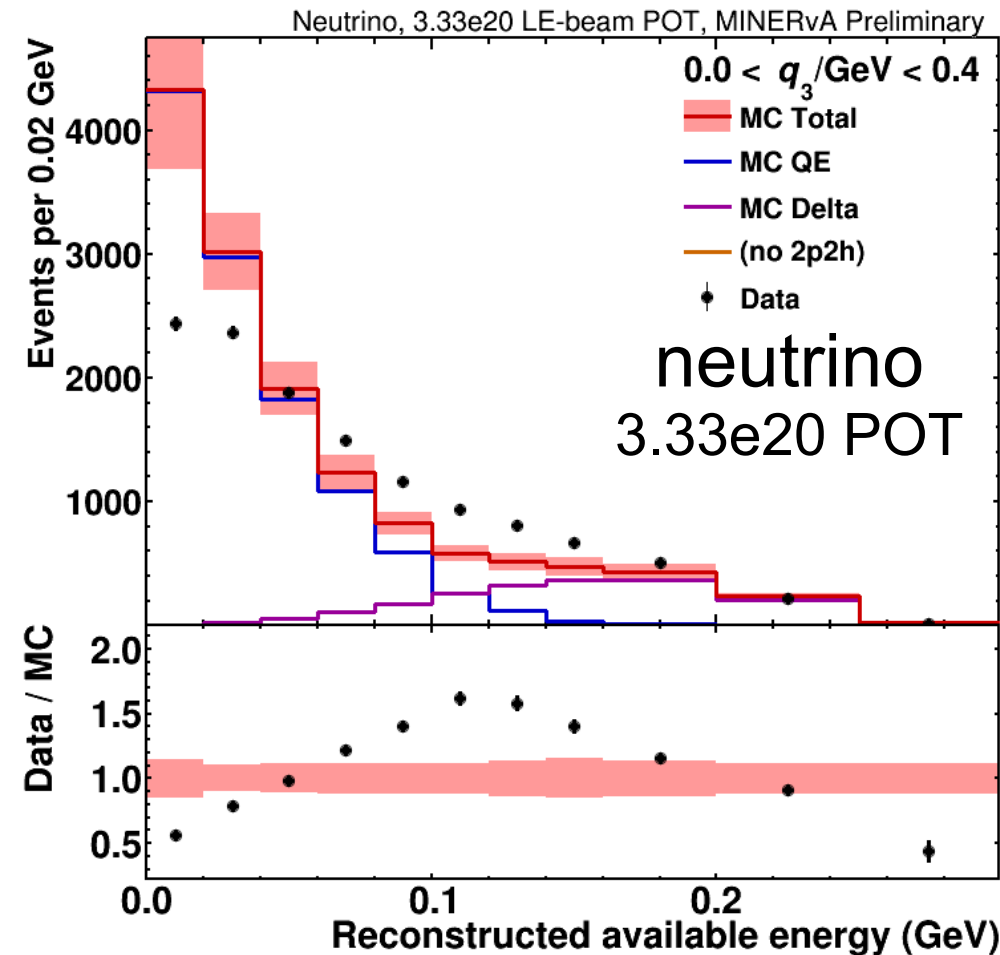
Is the chisquare better? Can a different model do better?

Did the model change affect QE, Dip, or Delta region?

$q_3 < 0.4$ GeV, GENIE, pion base, no RPA, no 2p2h

$X_2 = 407$ for 21 bins

$X_2 = 245$ for 19 bins



Rodrigues, Demgen, Miltenberger
et al. [MINERvA] PRL 116 071802

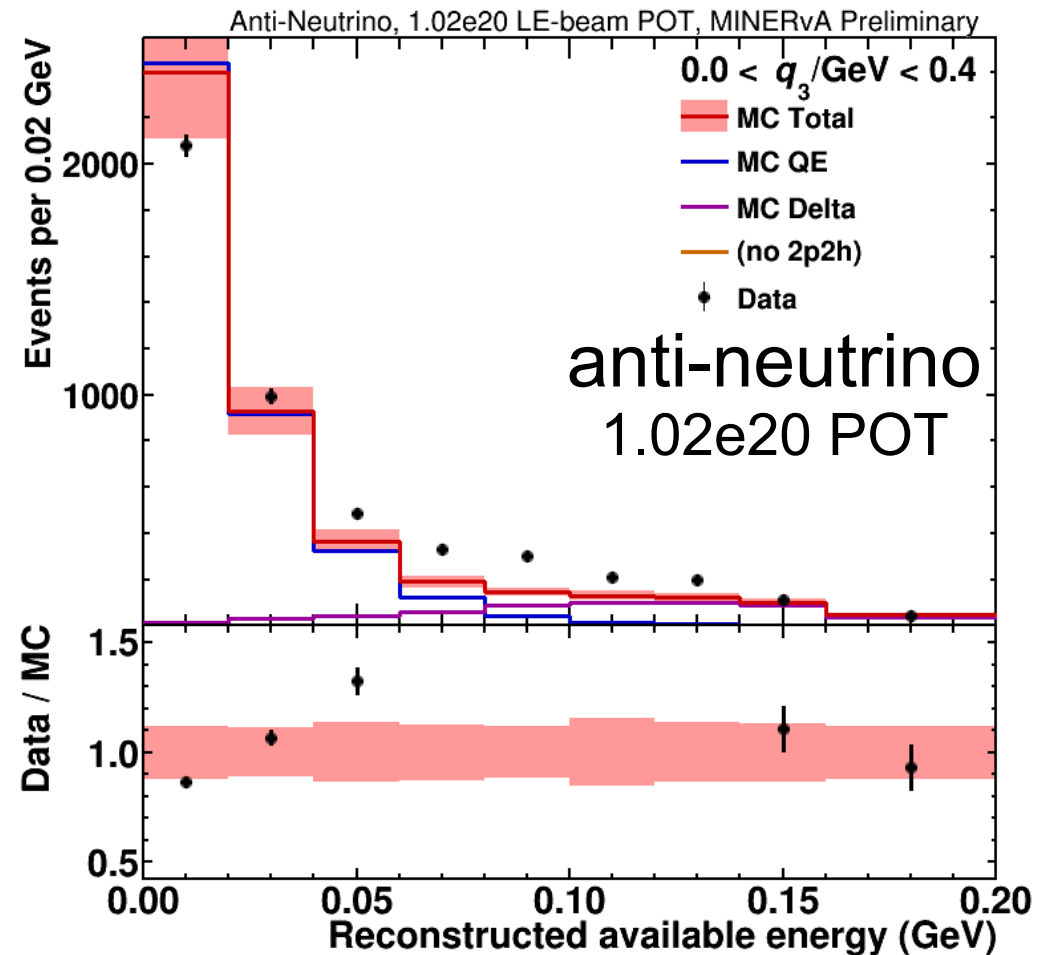
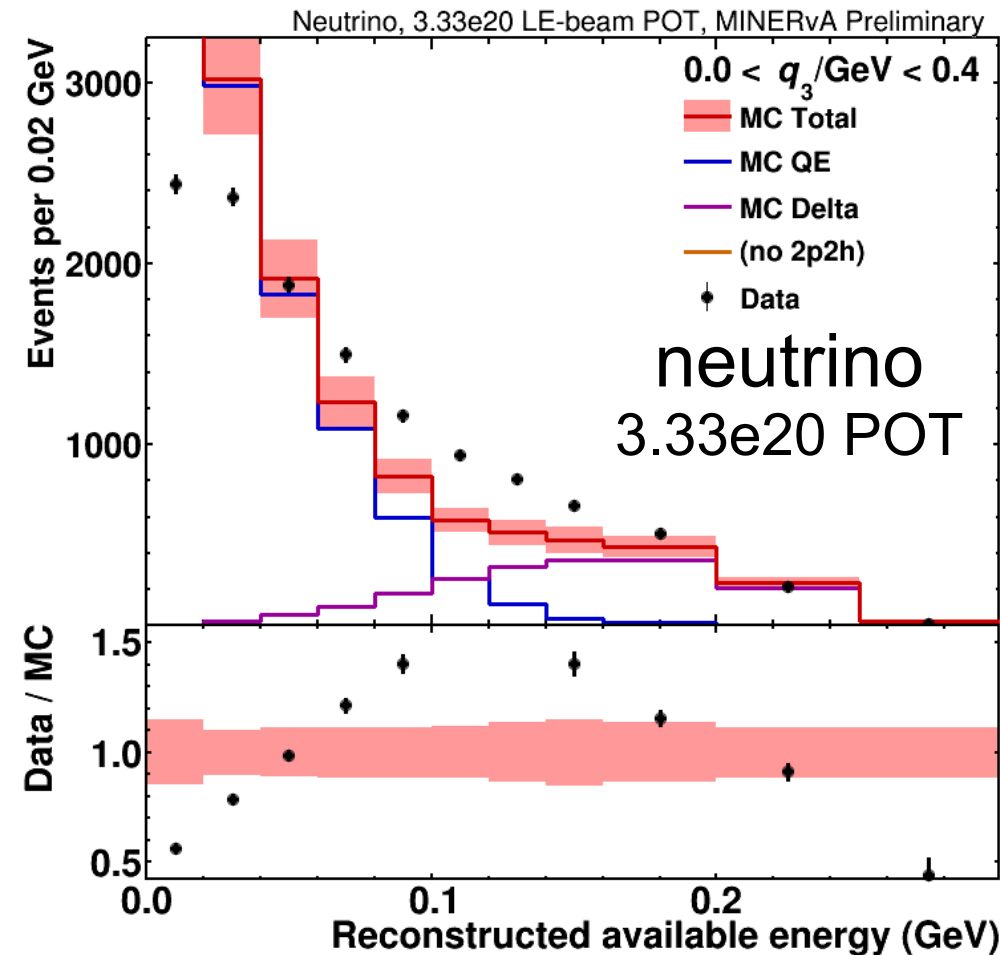
new for NuInt17
equivalent anti-neutrino distribution
neutrons dominate final state

Next slide is same data and model, just zoomed in to see detail

GENIE, pion base, no RPA, no 2p2h, zoom Y axis

X2 = 407 for 21 bins

X2 = 245 for 19 bins



Rodrigues, Demgen, Miltenberger
et al. [MINERvA] PRL 116 071802

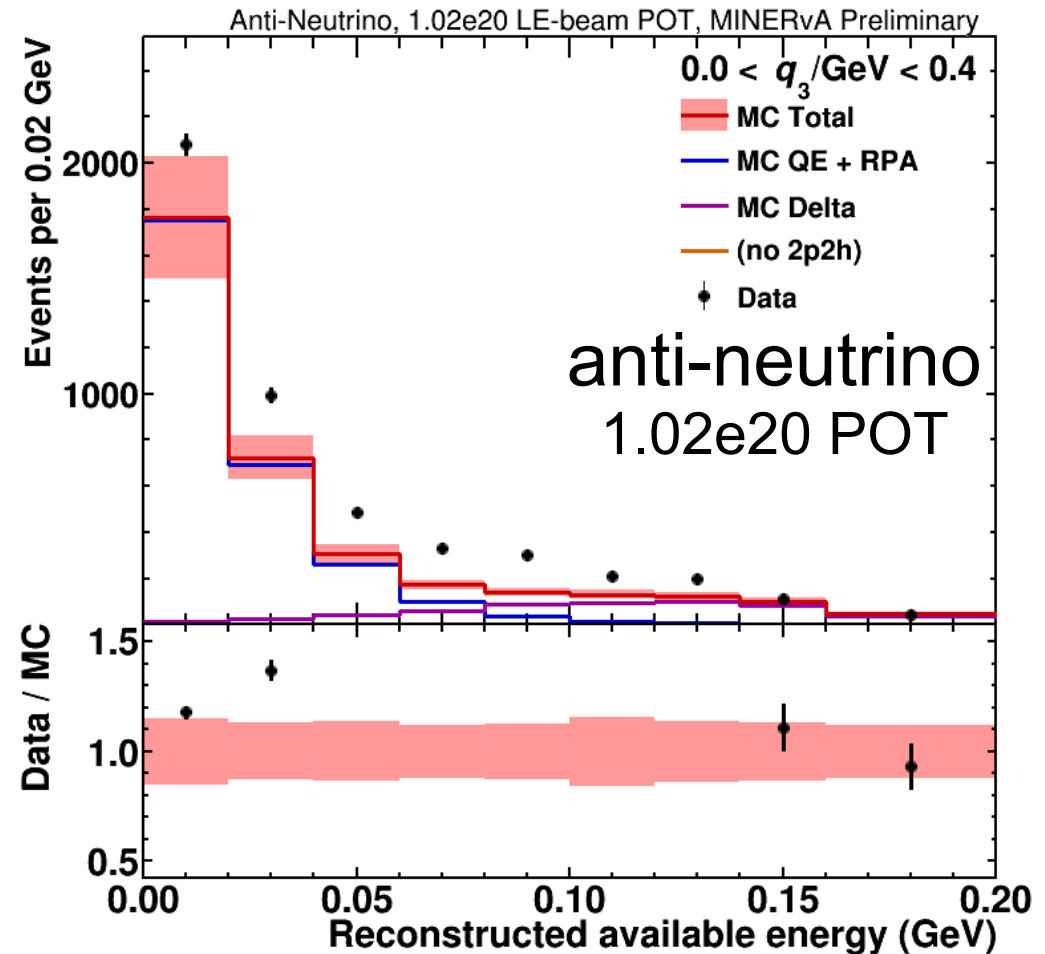
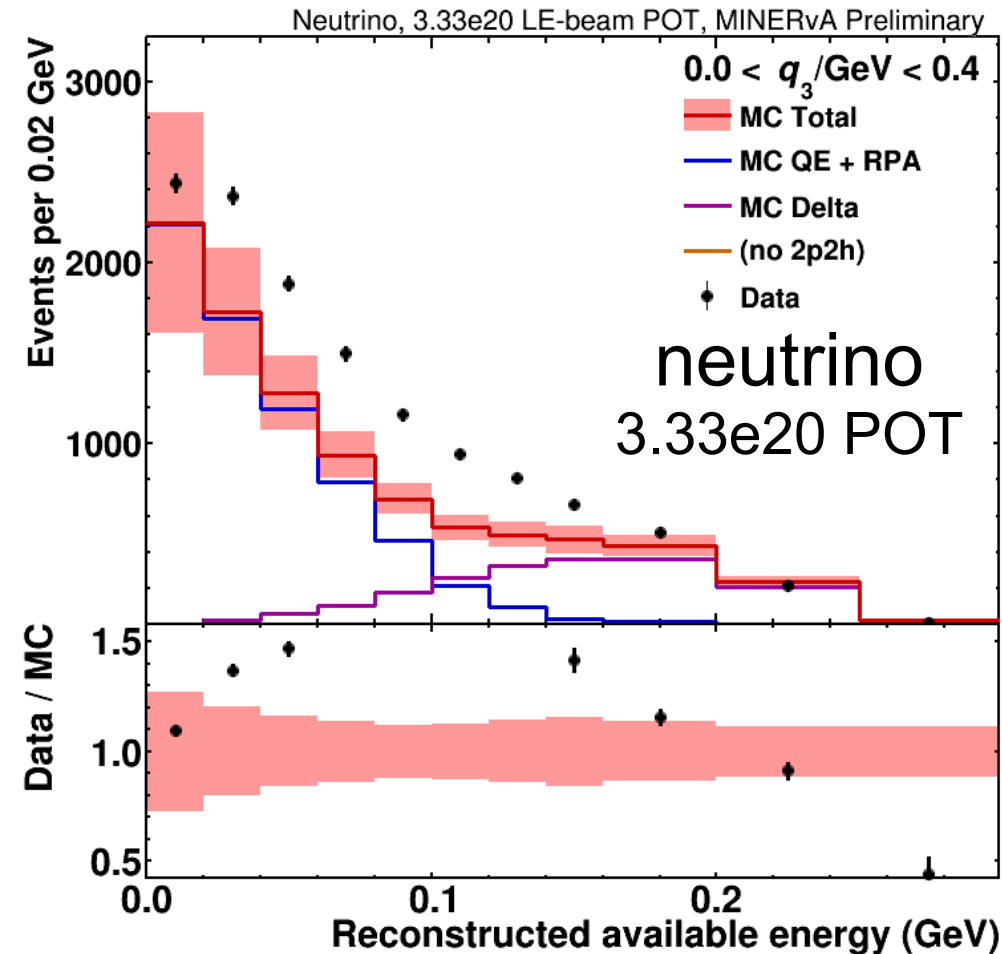
new for NuInt17
equivalent anti-neutrino distribution

Same as the previous slide, but zoomed in.
Budget 20 seconds each, two comments per slide,
take questions at the end (in about four minutes).

GENIE, pion base, RPA, no 2p2h

X2 = 227 for 21 bins

X2 = 237 for 19 bins

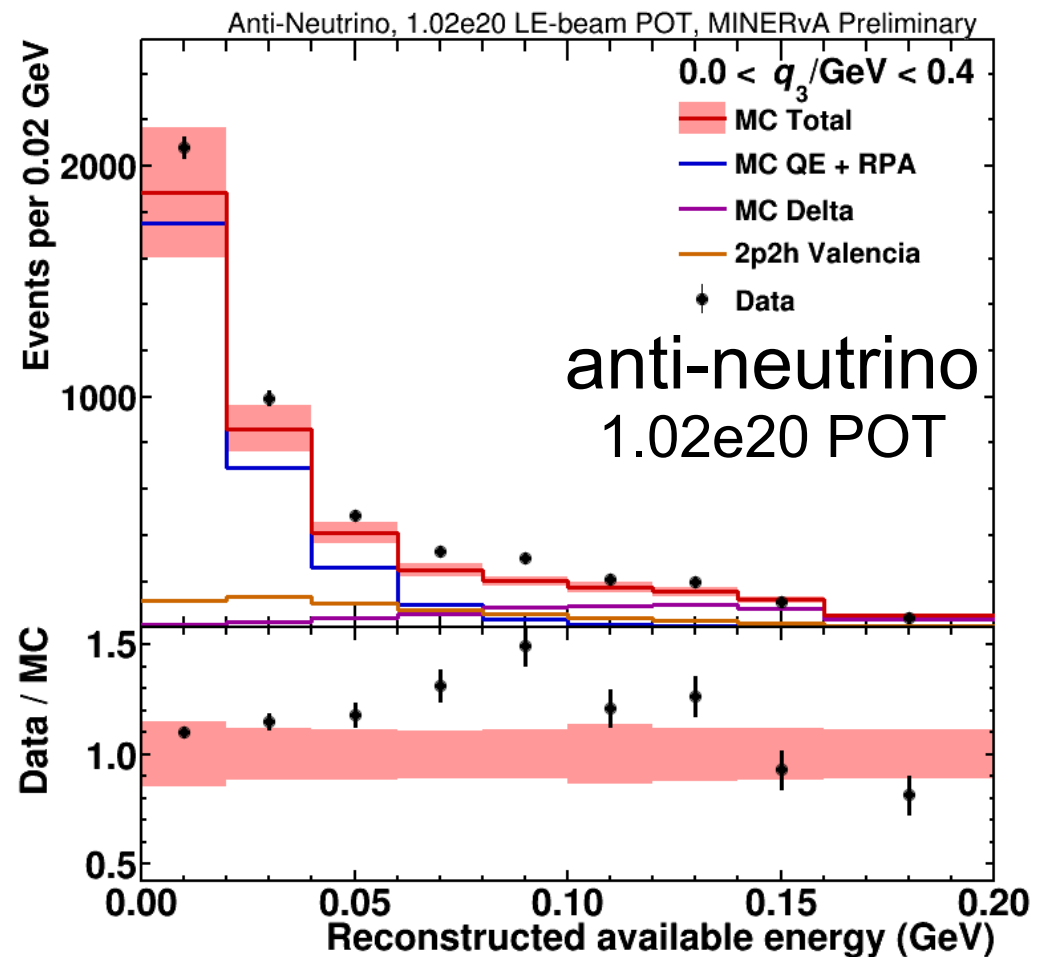
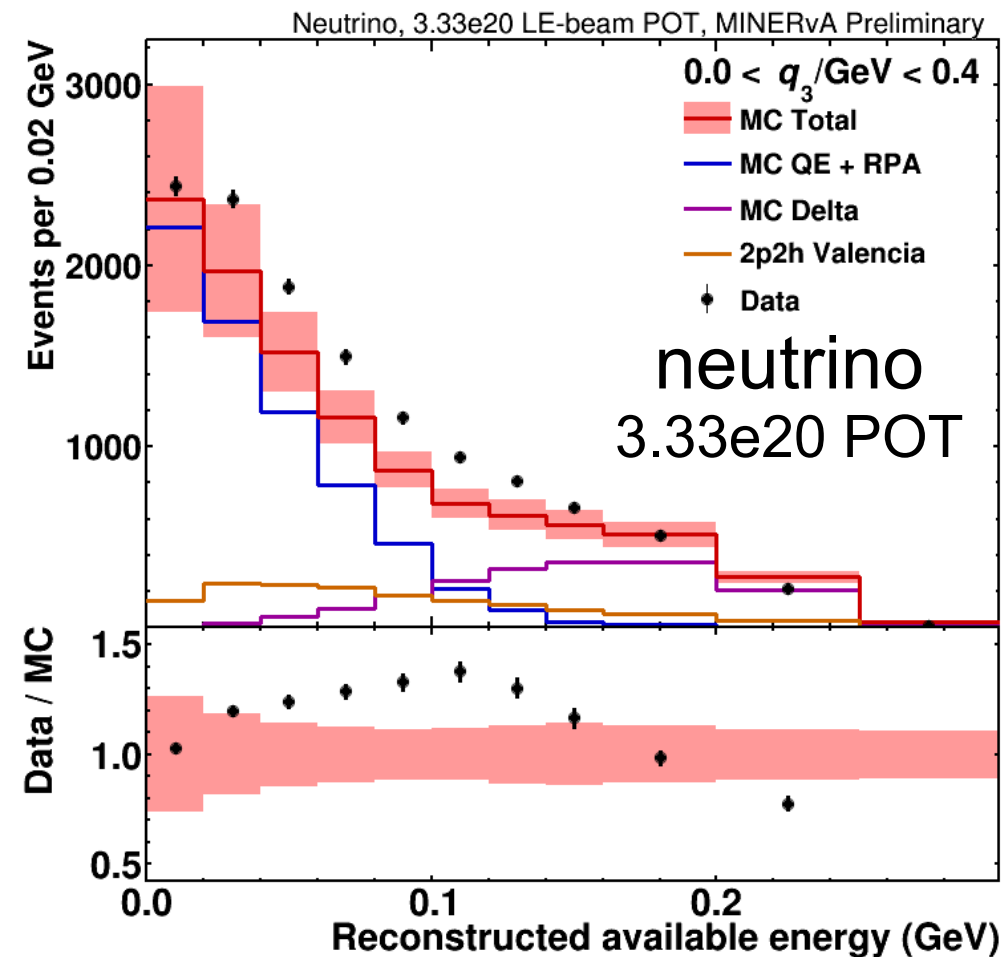


Add (updated) Valencia RPA weight and model error band
Valverde, Amaro, Nieves PLB 638 (2006) 325 with unpub. followup by F. Sanchez
plus **muon capture uncertainty** and implementation R. Gran, arXiv:1705.02932

GENIE, Pion base, RPA, Valencia 2p2h

X2 = 138 for 21 bins

X2 = 84 for 19 bins



Add Valencia 2p2h, improves the dip region

Nieves, Ruiz Simo, Vicente Vacas PRC83 (2011) 045501

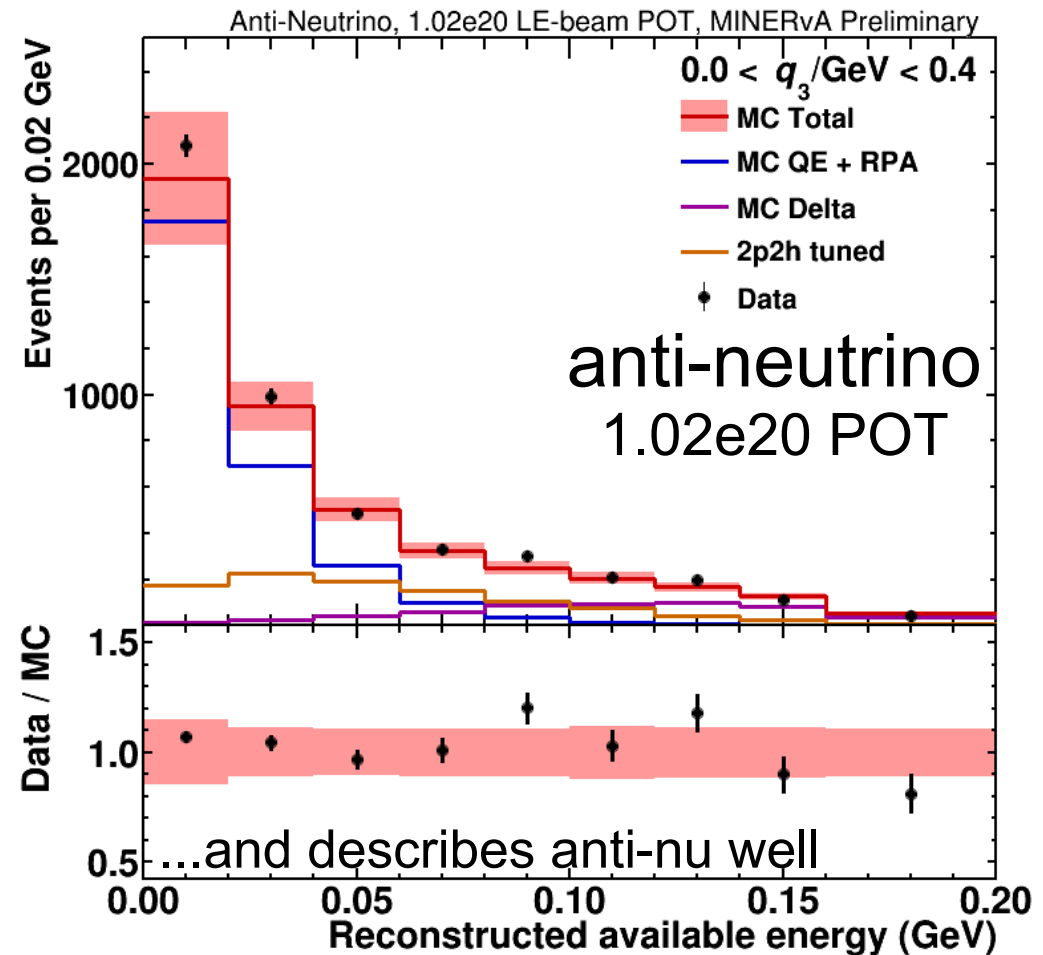
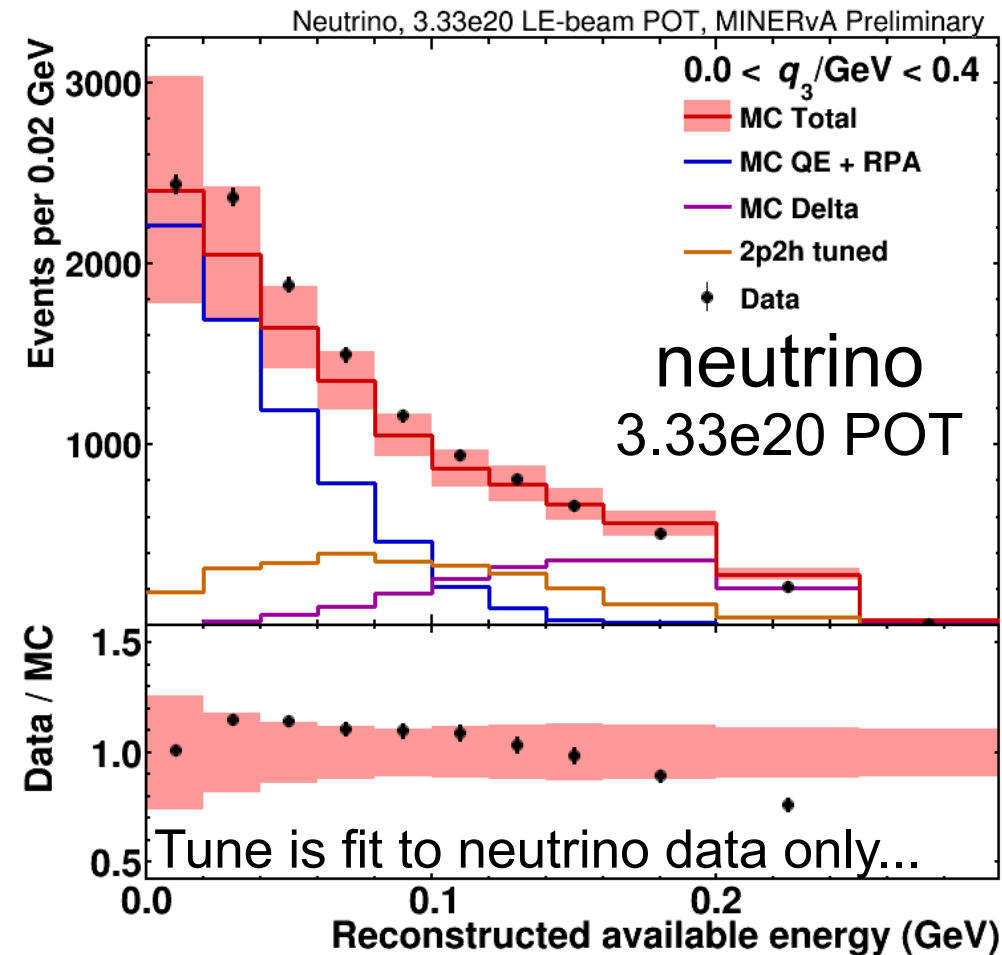
and R.G., Nieves, Sanchez, Vicente Vacas PRD 88 (2013) 113007

Same code as in Genie 2.12.6: J. Schwehr, R.G., D. Cherdack, arXiv:1705.02932

GENIE, Pion base, RPA, 2017 Tuned 2p2h

X2 = 76 for 21 bins

X2 = 50 for 19 bins



New: weighting up the 2p2h events with a 2D Gaussian weight

this base tune designed to empirically “Fill in” the dip region

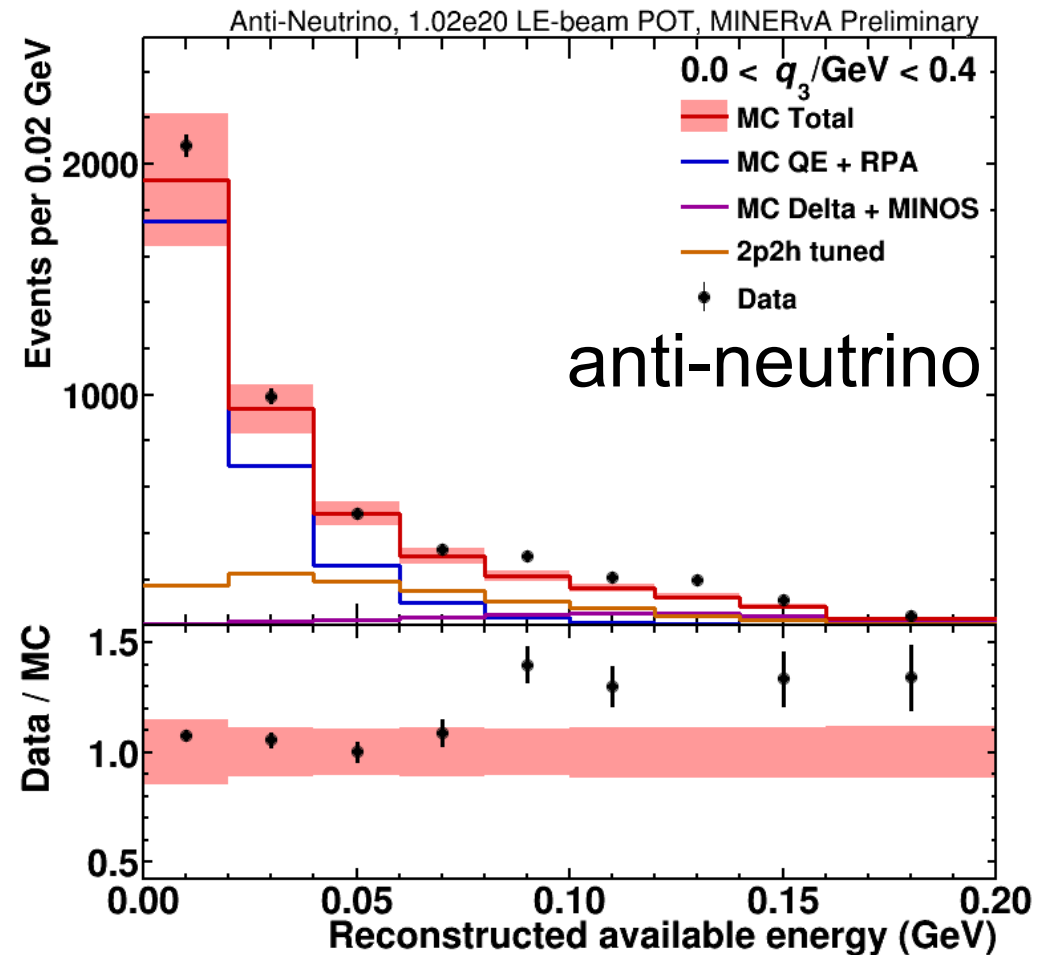
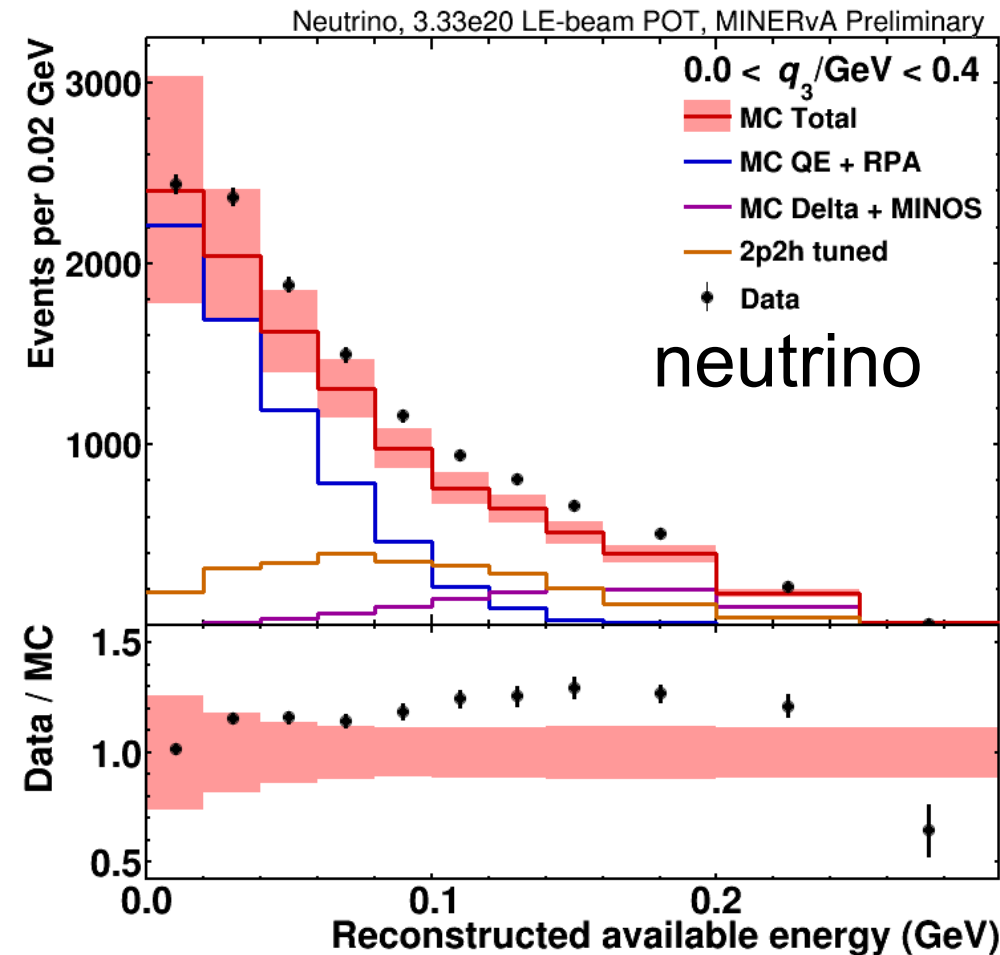
not whole kinematic range. Adds ~50% overall, but x2 in dip region

More on this in upcoming slides, and D. Ruterbories poster⁵⁶

GENIE, RPA, 2017 Tuned 2p2h, MINOS low-Q2 res

X2 = 106 for 21 bins

X2 = 132 for 19 bins

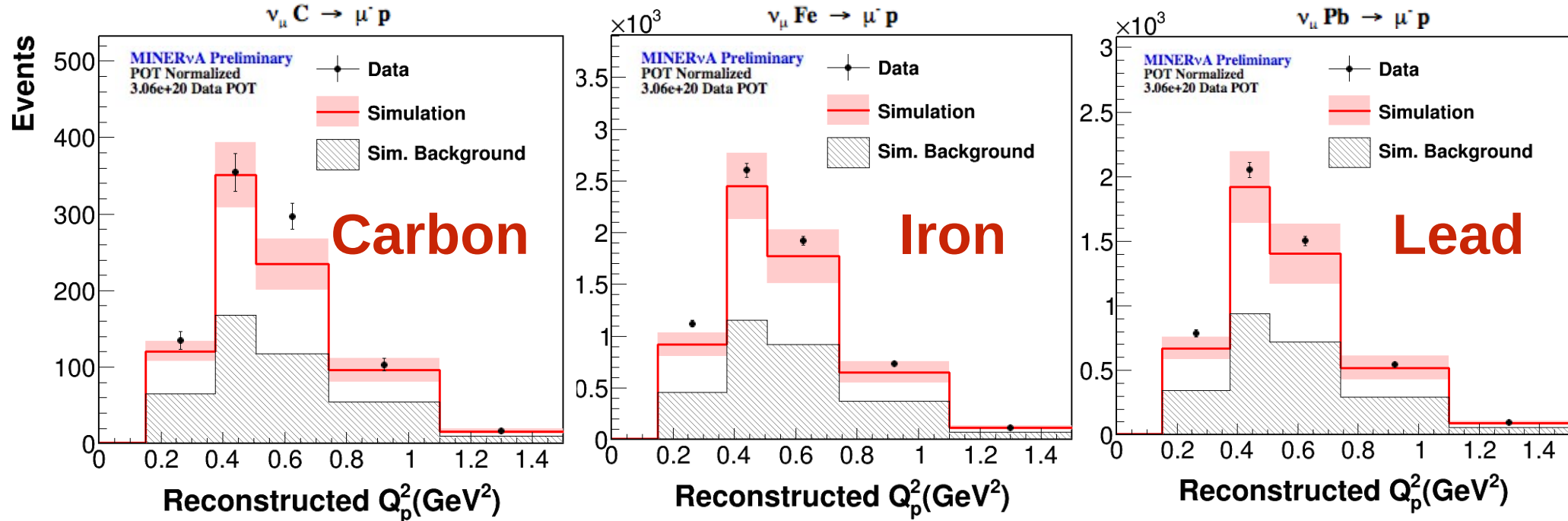


Add low Q2 suppression (RPA-like?) to all GENIE resonances
prescription from Minos nu+Fe sideband tune

Adamson, et al. PRD 91 (2015) 012005

This $r(Q^2)$ weight from Fe apparently is not quite right for CH
TOO MUCH, it goes to far.

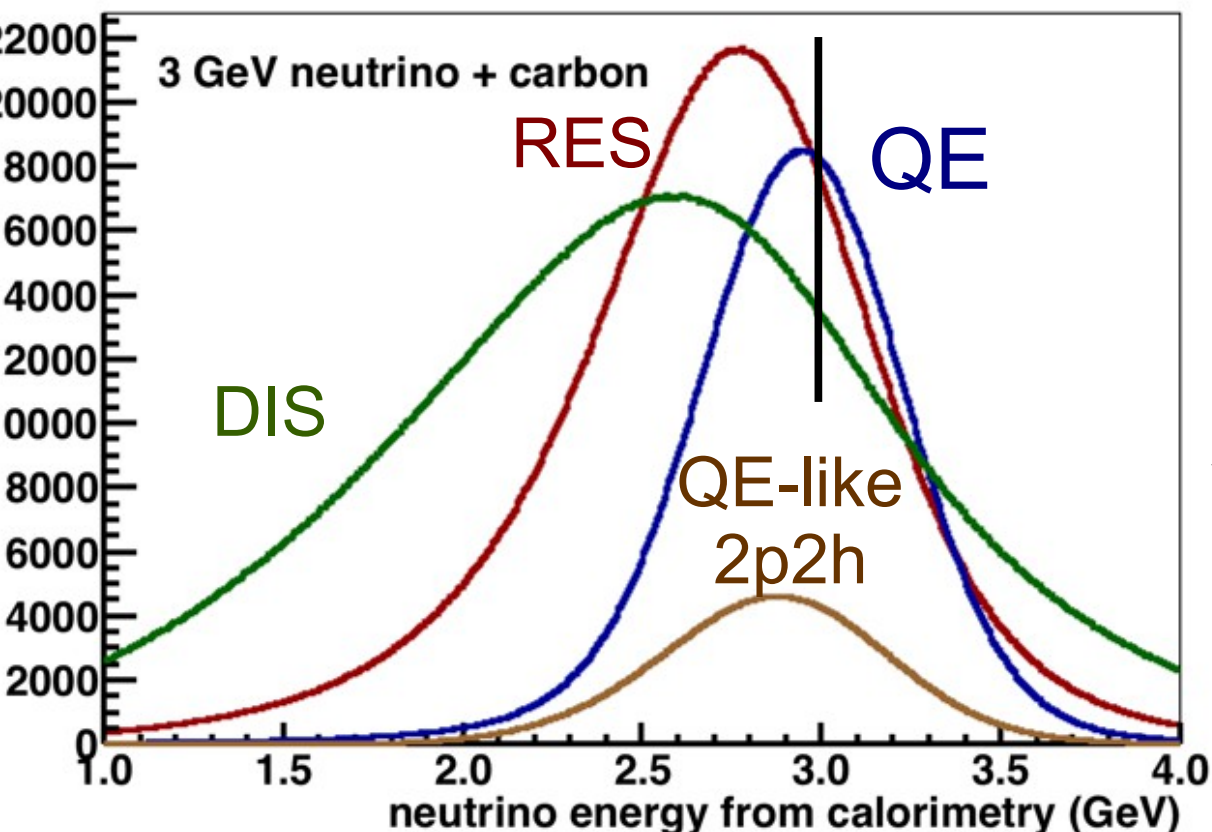
Reconstructed Proton Q2 (or proton kinetic energy)



Tuned background includes non-QE processes (2p2h) and scintillator events that were reconstructed in Pb, Fe, C these distributions look ok so far.

In a couple slides I'll show background subtracted, unfolded, differential cross section.

Method for getting the wrong** Ev: Calorimetry



NOvA, MINOS, DUNE method

Using MINERvA-like resolution
for muon reconstruction
and proton, pion calorimetry

Why are RES and DIS biased?

0.025 to 0.050 from unbinding
rest is neutron energy

Easy: just measure all the energy lepton + hadrons

Easy: (probably) gives the right answer if you saw them all

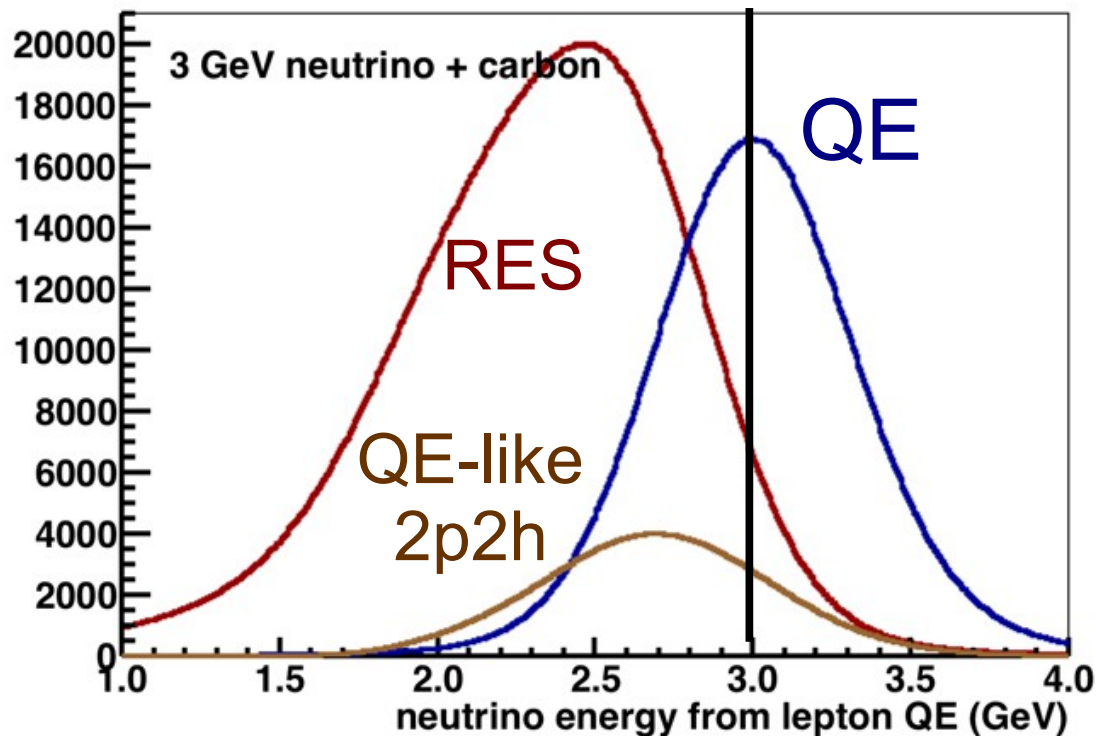
Hard: really? how do you know what you didn't see?

Harder: what you don't see is different for nu, anti-nu

**if we accurately model the hadron final state, its okay
need model/measurement/constraint on not-available energy

Method for getting the wrong** E_ν : QE hypothesis

T2K + HyperK + miniBooNE



reconstructed E_ν
for a sample of non-QE
simulated 2p2h events
(described later in talk)
with actual $E_\nu = 3.0$ GeV
includes rough
MINERvA-like resolution

Easy: you can do this measuring the lepton (μ or e) only

Easy: (probably) gives the right answer if it really was QE

Hard: gives demonstrably wrong answer if not QE

Harder: wrong answer depends on kinematics

**if we accurately predict the non-QE component, its okay
depends on selection effects cutting the non-QE
real need model/measurement/constraint on non-QE 60